Michael R. Matthews *Editor*

International Handbook of Research in History, Philosophy and Science Teaching

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Chapter 1
Introduction: The History, Purpose and Content of the Springer *International Handbook of Research in History, Philosophy and Science Teaching*

Michael R. Matthews

This is the first handbook to be published that is devoted to the field of historical and philosophical research in science and mathematics education (HPS&ST). Given that science and mathematics through their long history have always been engaged with philosophy and that for over a century it has been recognised that science and mathematics curriculum development, teaching, assessment and learning give rise to many historical and philosophical questions, it is unfortunate that such a handbook has been so long coming.

This work is an international endeavour with its 76 chapters being written by 125 authors from 30 countries. Each chapter has benefited from reviews by up to six scholars and has undergone multiple revisions. More than 300 reviewers, from the disciplines of history, philosophy, education, psychology, mathematics and natural science were willing to contribute their time and expertise to the project. Volunteer copyeditors, with command of both the subject area and English expression, also contributed to the final form of the chapters. A great debt is owed by authors, the research community and readers to these reviewers and copyeditors for their anonymous and unrewarded work. The handbook has grown directly from the Springer journal *Science & Education: Contributions from History and Philosophy of Science and Mathematics.*[1]

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[1] The journal was the first such research journal devoted exclusively to HPS-informed research in science and mathematics education. Nearly all of the 125 authors have published in the journal and the 300+ reviewers have been drawn from the journal's pool of 900+ reviewers (these can be seen at http://ihpst.net/journal/reviewers/list-of-reviewers/). But the century of research covered by the contributors extends far beyond the pages of the journal, as can be seen by looking at the Reference lists of the chapters.

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1.1 The International History, Philosophy and Science Teaching Group

The journal in turn is associated with the International History, Philosophy and Science Teaching Group that held its first conference in 1989 at Florida State University, with subsequent conferences held biennially.[2] The conferences are attended by historians, philosophers, cognitive psychologists, scientists, mathematicians, education researchers and teachers all of whom have contributed greatly to the formation of a vibrant, congenial, multidisciplinary, international research community. This community forms the core of the authors and reviewers for the handbook; the handbook is a concrete expression of the interests and scholarly work of this IHPST community.

The structure, contents and rationale of the handbook have a lineage that goes back to the very beginnings of the IHPST group, and thus there is benefit in giving an account of its early history. In 1987, I took sabbatical leave at the Philosophy Department of Florida State University in order to pursue with David Gruender some research on Galileo's pendulum discoveries. While in Tallahassee, I attended a large Newton celebration sponsored by the AAAS to honour the tri-centenary of the publication of Newton's *Principia*. Returning from that Washington meeting, I casually mentioned to Jaakko Hintikka that 'it is a pity that science teachers do not attend such meetings, there was so much there that would have been of interest and use to them'. In response, Hintikka, the editor of *Synthese*, the major Kluwer philosophy of science journal, suggested that I edit a special issue of journal on the subject of 'History, Philosophy and Science Teaching' (HPS&ST). This casual exchange was to be the seed of the IHPST group, the journal *Science & Education* and, 25 years later, this handbook.

I began writing, at a time before email and the web, to scholars I knew who had HPS&ST interests and asking them to send me names of others they knew; this was a sort of academic 'pyramid' scheme. The result was a very large and impressive collection of manuscripts written by historians, philosophers, scientists, cognitive scientists and educators.[3] With far too many manuscripts for a single issue of *Synthese*, I reached agreement with other journal editors to publish eight special

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[2] These have been Queen's University Kingston (1992), University of Minnesota (1995), University of Calgary (1997), University of Pavia (1999), Denver (2001), University of Manitoba (2003), University of Leeds (2005), University of Calgary (2007), University of Notre Dame (2009), Aristotle University Thessaloniki (2011) and University of Pittsburgh (2013). Since 2010, these international conferences have been augmented by regional conferences in Latin America: Maresias Beach, Brazil, in 2010, Mendoza Argentina (2012) and Asia: Seoul National University (2012) and National Taiwan Normal University (2014).

[3] Among those who contributed manuscripts were Joan Solomon, Rodger Bybee, Manuel Sequeia, Laurinda Leite, Harvey Siegel, Martin Eger, Nancy Nersessian, Ernst von Glasersfeld, Joseph Pitt, Jim Garrison, Ian Winchester, Michael Ruse, Arthur Stinner, James Cushing, Stephen Brush, Arnold Arons, Michael Otte, Dimiter Ginev, Derek Hodson, Fritz Rohrlich, Mansoor Niaz, George Kauffman, Pinchas Tamir and Wim van der Steen.

issues of different journals devoted to the subject. These together constituted the first ever journal issues with the title ‘History, Philosophy and Science Teaching’.[4]

David Gruender, and Ken Tobin who was newly appointed to Science Education at Florida State University, suggested bringing authors and readers together for an HPS&ST conference. The resulting meeting, with the generous support of the National Science Foundation and of Florida State University, was held in November 1989. There were 180 participants including nearly all of the above-listed journal contributors. Two large volumes of Proceedings – *The History and Philosophy of Science in Science Teaching*, edited by Don Herget and containing 75 papers – were produced.[5] Others gave papers or contributed to the conference.[6] With the special issue articles, the *Proceedings* and other papers, there was an abundance of material with which participants could engage.

Fortunately, in the process of ‘networking’ for the conference, contact was made with Fabio Bevilacqua from the University of Pavia and who was chairperson of the Interdivisional Group on History of Physics of the European Physical Society.[7] Although from a Physics Department, Bevilacqua had completed his PhD in the History and Philosophy of Science Department at Cambridge University, with a thesis supervised by Mary Hesse and Gerd Buchdahl.

The European Group’s Pavia conference was held under the auspices of the International Commission on Physics Education (ICPE), and it explicitly tried to build on an earlier ICPE conference (1970) on ‘History in the Teaching of Physics’ whose published Proceedings were edited by Stephen G. Brush and Allen L. King. The 1983 Pavia conference organisers, Fabio Bevilacqua and Peter Kennedy, wrote in the *Pavia Conference Proceedings* that ‘we began to feel that to confine the discussion only to the history of physics was unduly restrictive and that philosophy and sociology had much to contribute in seeking to show a more complete picture of physics’. From the beginning, the IHPST group had the same conviction but applied to all the sciences.

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[4] The journals were *Educational Philosophy and Theory* 20(2), (1988); *Synthese* 80(1), (1989); *Interchange* 20(2), (1989); *Studies in Philosophy and Education* 10(1), (1990); *Science Education* 75(1), (1991); *Journal of Research in Science Teaching* 29(4), (1992); *International Journal of Science Education* 12(3), (1990); and *Interchange* 24(1–2), (1993).

[5] The *Proceedings* included papers written by, among others, Sandra Abell, Angelo Collins, Jere Confrey, George Cossman, Zoubeida Dagher, Peter Davson-Galle, Arthur Lucas, Michael Akeroyd, James Gallagher, Teresa Levy, Richard Duschl, Thomas Settle, Hugh Petrie, Robert Hatch, Jane Martin, Joseph Nussbaum, Stellan Ohlsson, Luise Prior McCarty, Edgar Jenkins, Jacques Désautels, Marie Larochelle, Thomas Wallenmaier, Alberto Cordero, Sharon Bailin, Jim Stewart and Carolyn Carter.

[6] Among these were Peter Slezak, Robert Carson, Douglas Allchin, Judith Kinnear, Michael Clough, Hans O. Anderson, Penny Gilmer, Richard Grandy, Jack Lochhead, Zofia Golab-Meyer, James Wandersee, Matilde Vicentini, Peter Taylor, Brian Woolnough and Joseph Novak.

[7] The European group had already held education conferences in Pavia (1983), Munich (1986) and Paris (1988). Subsequently, it would hold conferences in Cambridge (1990), Madrid (1992), Szombathely (1994) and Bratislava (1996) with printed Proceedings being produced for each of these meetings. In 1999, the Group’s conference was held jointly with the IHPST conference in Pavia and Lake Como.

Bevilacqua attended the Tallahassee meeting (and is remembered for his commanding role as the scarlet-cloaked Cardinal Bellarmine in Joan Solomon's conference production of 'The Trial of Galileo' in which Michael Ruse is remembered for his Galileo performance). Connection with the European group contributed greatly to making IHPST less a US-Anglo grouping and more robustly an international group. On account of the uncommon spread of disciplines represented and its conviviality, Tallahassee was an overwhelmingly successful and much-remembered meeting. The participants constituted an informal IHPST group for which I became the newsletter editor.

There are many things that can be said about the background and deliberations of the Tallahassee meeting. The first is that although the bulk of the conference was concerned with the traditional liberal education agenda of how HPS can enhance and improve the teaching of science, it did occur at the same time as the 'Science Wars' were erupting in the HPS and Science Studies communities; it was an intellectually exciting and polarising time. The wars erupted on many fronts - in sociology of science the Edinburgh 'Strong Programme' was gaining academic traction fuelled in part by relativist and constructivist interpretations of Thomas Kuhn; many feminist and multicultural critiques of science and of orthodox philosophy of science had been published; postmodernist outlooks were being manifested in many departments.[8]

To some degree, the Science Wars, Postmodernism and Realist versus Constructivist debates were played out at the conference. A plenary session was devoted to the Constructivist debate; it was chaired by Ken Tobin and contributed to by Jaques Désautels, Ernst von Glasersfeld and David Gruender. Gruender's paper was titled: 'Some Philosophical Reflections on Constructivism', and he wrote: 'It is impossible to look at current literature dealing with the education of teachers, especially in science and mathematics, without noticing the galvanizing effects of the newly introduced theory of "constructivism".' He went on to caution that: 'this whole approach of defining knowledge in terms of environmental feedback leading to constructs which better enable the knower to survive in the environment raises serious theoretical issues of its own. And this is so whether one prefers the version offered by Piaget or by Dewey'.

There were divisions at the conference about the epistemological, ontological and pedagogical merits of constructivism, a division between two intellectual tendencies, loosely labelled Realism and Constructivism, yet pleasingly the conference was marked by convivial and congenial exchanges on the subject. There was wide agreement about the benefit of constructivist pedagogy, but disagreement

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[8] By the time of the conference, the work of Jean-Francȩis Lyotard, Michel Foucault, Michael Mulkay, Bruno Latour, Harry Collins, Sandra Harding, Evelyn Fox Keller, Andrew Pickering, David Bloor, Michael Lynch, Steve Woolgar, Donna Haraway, Sal Restivo, Mary Belenky and Jacques Derrida had been published, much read and having some influence on theorists in education circles. Ernst von Glasersfeld, the 'radical constructivist', was an energetic participant at the conference and a contributor to the *Synthese* special issue.

about its commonly related epistemological and ontological claims. This tension has carried through the subsequent history of the group and the journal. For the journal debate began with Wallis Suchting's severe paper 'Constructivism Deconstructed' and Ernst von Glasersfeld's 'Reply' both in the first volume (1992), and continued through a special double issue on the subject in the sixth volume (1997), and into subsequent volumes right through to the present handbook chapter.

A second noteworthy thing about the Tallahassee conference and in the collection of journal special issues is the part played by cross-disciplinary training of individuals involved. In particular, the conference and journal special issues came about because an Italian Physics lecturer had completed an HPS degree at Cambridge, and an Australian Education lecturer had completed a philosophy degree at the University of Sydney and had taken sabbatical leaves in the Boston University and FSU Philosophy departments. Other participants had comparable cross-disciplinary backgrounds. For everyone, the value of scientists and science and mathematics educators working with philosophers, historians, cognitive psychologists and others was immediately apparent.

The value of cross-disciplinary training, or at least cooperation, was a lasting lesson that has informed the subsequent history of IHPST, the journal *Science & Education* and, 25 years later, the organisation of this handbook. It is a lesson that perhaps should inform the training and preparation of science educators where too often the standard trajectory is Science followed by Education and then educational research without mastering any other foundation discipline such as Philosophy, Psychology, History or Sociology.

After 20 years of productive but informal existence without office bearers, the IHPST group was formalised in 2007 at its Calgary conference. A constitution was adopted, elections for a governing council were held and the following aims adopted:

(a) The utilisation of historical, philosophical and sociological scholarship to clarify and deal with the many curricular, pedagogical and theoretical issues facing contemporary science education. Among the latter are serious educational questions raised by Religion, Multiculturalism, Worldviews, Feminism and teaching the Nature of Science.
(b) Collaboration between the communities of scientists, historians, philosophers, cognitive psychologists, sociologists, and science educators, and school and college teachers.
(c) The inclusion of appropriate history, philosophy and sociology of science courses in science teacher-education programmes.
(d) The dissemination of accounts of lessons, units of work and programmes in science, at all levels, that have successfully utilised history, philosophy and sociology.
(e) Discussion of the philosophy and purposes of science education, and its contribution to the intellectual and ethical development of individuals and cultures.

This handbook contributes to realising these aims.

1.2 *Science & Education* Journal

The journal began during a conversation at a US Philosophy of Education conference in 1990 with Peter de Liefde, then Kluwer Education Editor. Kluwer did not then have a presence in science education, and he saw the possibility of building on the IHPST newsletter and community in creating a new scholarly journal. With a great deal of assistance from many people who agreed to be on the editorial committee, the journal commenced publication in 1992. In its beginnings, the journal tried to meet the highest standards; pleasingly, it was able to publish research by deservedly well-known scholars from the fields of science education, mathematics education and history and philosophy of science.[9] It is no exaggeration to say that the disciplinary spread and quality of authors had not before been seen in education journals. The multidisciplinary pattern and high standards were maintained in the following 20+ years where well-known scholars have been published who may not otherwise have addressed issues in science and mathematics education.[10]

Since its beginning in 1992 with four numbers per year, the journal has grown both in size and in scholarly recognition. In 1997, it moved to six numbers, in 2003 to eight numbers and in 2007 to ten numbers per volume; in 2011, there were 108,650 article downloads from its Springer site.

1.3 The Handbook Project

The handbook project began in 2010 during discussion with Bernadette Ohmer, the Springer Education Editor (Springer having taken over Kluwer in 2005) about how best to celebrate the 20th anniversary of the founding of *Science & Education*. It was soon obvious to both of us that a HPS and Science Teaching Handbook was the best and most useful way to mark the journal's publication milestone. This began

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[9] In the first year, papers by, among others, Wallis Suchting, Paul Kirschner, Mark Silverman, Derek Hodson, Martin Eger, Helge Kragh, Maryvonne Hallez, Israel Scheffler, Alberto Cordero, Creso Franco and Dominique Colinvaux-de-Dominguez were published. In the second year, papers by, among others, Richard Kitchener, Gerd Buchdahl, Jack Rowell, Walter Jung, Henry Nielsen, Harvey Siegel, Lewis Pyenson, Victor Katz, Bernard Cohen, Nancy Brickhouse and Enrico Giannetto. The third year saw papers by, among others, John Heilbron, Peter Machamer, Michael Martin, Robert S. Cohen, Peter Slezak, Andrea Woody, James Garrison and Jane Martin. A number of these papers had their origins in conferences of the Interdivisional Group on History of Physics of the European Physical Society.

[10] Philosophers who have published in the journal include John Worrall, Alan Musgrave, Hasok Chang, Peter Machamer, Michael Martin, Noretta Koertge, Robert Crease, Patrick Heelan, Robert Nola, Alan Chalmers, Mario Bunge, Robert Pennock, Steve Fuller, Jane Roland Martin, Howard Sankey, Demetris Portides, Hugh Lacey, Gürol Irzik, Cassandra Pinnick, Joseph Agassi, Michael Ruse, David Depew, Massimo Pigliucci and many more. Historians whose work has been published have included John Heilbron, Lewis Pyenson, Roger Stuewer, William Carroll, Stephen Brush, Roberto de Andrade Martins, Bernadette Bensaude-Vincent, Ronald Numbers, John Hedley Brooke, Diane Paul and many more.

the three-year process of contacting, inviting, structuring, writing, reviewing, revising, more reviewing and writing that has led to the 2014 publication of the handbook.

For the historic record and for understanding the contents of the Handbook, it is worth repeating the initial invitation to authors:

> The guiding principle for the *Handbook* chapters is to review and document HPS-influenced scholarship in the specific field, to indicate any strengths and weaknesses in the tradition of research, to draw some lessons from the history of this research tradition, and to suggest fruitful ways forward. … The expectation is that the handbook will demonstrate that HPS contributes significantly to the understanding and resolution of the numerous theoretical, curricular and pedagogical questions and problems that arise in science and mathematics education.

Authors accepting the invitation to contribute received a reply saying:

> The expectation is that [the Handbook] will make the history and philosophy of science (and mathematics) a more routine and expected part of science and mathematics teaching, teacher education and graduate research programmes.
>
> My own view is that much the same arguments developed in the handbook will apply to teaching and research in any discipline – economics, history, geography, psychology, theology, music, art, cognitive science, literature and so on. That is, to educate someone in any discipline requires a grasp of the history and philosophy of the discipline; and to conduct serious research in the teaching and learning of any discipline will likewise require historical knowledge and philosophical competence. Hopefully this handbook might inspire others to repeat the exercise for other disciplines.

It will be for readers to judge how significant the handbook's contribution is to science and mathematics education. Readers will have their own view on whether teaching a subject requires some knowledge of the history and philosophy of the subject, and they will also have their own view on the degree to which research in the teaching and learning of science and mathematics requires historical and philosophical competence. Handbook authors affirm both positions. If their arguments are convincing, then they have clear implications for teacher education and for doctoral programmes that prepare education researchers.

1.4 Handbook Structure

Focussed discussion of HPS&ST questions was given a significant boost in the nineteenth century when Ernst Mach, the great German physicist, philosopher, historian and educator, founded in 1887 the world's second science education journal - *Zeitschrift für den physikalischen und chemischen Unterricht*.[11] In the USA, John Dewey in the 1920s explicitly addressed HPS&ST issues, later taken up in the 1950s and 1960s by, among others, James Conant, Gerald Holton, Stephen G. Brush, Leo Klopfer, Robert S. Cohen, Joseph Schwab and Arnold Arons.

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[11] The first such journal was *Zeitschrift für mathematischen und naturwissenschaftlichen Unterricht* which began publication in 1870. It was edited by J. C. V. Hoffmann, a secondary school teacher in the Saxony mining town of Freiberg (thanks to Kathryn Olesko for this information).

In the UK, HPS&ST issues were addressed from the 1920s in books and articles by Frederick Westaway, Eric Holmyard and James Partington and subsequently by John Bradley, Joan Solomon and others. The same questions have been investigated in Spanish, Portuguese, French, German, Italian, Finnish and other traditions. So there is an abundance of material to be covered and appraised in an HPS&ST handbook.

The first question in putting the handbook together was how to structure its contents. My choice was to group extant research into four sections:

Pedagogical Studies
Theoretical Studies
Regional Studies
Biographical Studies

1.4.1 Pedagogical Studies

The Pedagogical section was straightforward. Since Mach's time, educators have looked to history and philosophy in order to improve and make more interesting and engaging the classroom teaching of science and mathematics. Curriculum writers have likewise turned to the history and philosophy of both disciplines for guidance about the philosophical structure and epistemology of the subjects, and suggestions about the best order, from a psychological or maturation perspective, in which to present the subjects. For over a century, these endeavours have been pursued in Physics, Chemistry, Biology, Mathematics and more recently in the Earth Sciences, Astronomy, Cosmology and Ecology. Since, for instance, the 1920s HPS-informed articles have appeared in *The Journal of Chemical Education, The School Science Review* and *Science Education*; they might also be found at this early time in *The American Journal of Physics* and *Physics Education*.

The research literature on HPS and physics teaching is voluminous. This is perhaps to be expected given that Ernst Mach is the founder of formal, organised, published HPS&ST research and that all of the prominent physicists of the nineteenth and twentieth centuries were, like Mach, engaged by philosophy and wrote books on the subject. Handbook chapters cover each of the areas of Mechanics, Optics, Electricity, Relativity, Quantum theory, Energy and Thermodynamics. One need only mention these science fields to be reminded that major historical figures contributed to their development, and in each there were, and still are, serious philosophical issues and controversies. The specific case of pendulum motion is included as an example of how the understanding and teaching of even mundane areas of science can be illuminated and energised by knowledge of the history and philosophy of topic.

For over a century, there has been insightful writing on the history of chemistry and of course on some of the major advances and controversies in the discipline such as the phlogiston versus oxygen theory of combustion, formulation of the periodic table, uncovering of atomic structure and resultant theory, and organic compounds and their creation. Much has been written on the work of Priestley, Lavoisier, Dalton, Mendeleev, Davy, Kehulé, Pauling and other major contributors. There has also been a long history, since Edward Frankland and Henry Armstrong in the nineteenth century and Eric Holmyard between the wars, of serious efforts to utilise the history of chemistry in creating chemistry curriculum and improving chemistry teaching. Two chapters here deal with this research. In contrast, philosophers have not paid the same attention to chemistry, but over the past three decades this has changed, and there is now at least one journal dedicated to the subject, *Foundations of Chemistry*, and there have been important books published in the field. Philosophy was mostly implicit in the long decades of utilising history in chemistry education; it was made explicit in the 1960s by John Bradley, the Machian chemist, in his debates with Nuffield Scheme 'atomic modelists'. In this debate he lamented that: 'The young people of this country come hopefully to school asking for the bread of experience; we give them the stones of atomic models'.[12] Pleasingly, a handbook chapter deals with the now more conscious efforts to explicate philosophy of chemistry and to connect this with issues in chemistry education.

History and philosophy have a far more public face in the teaching of biology, this is especially so for the teaching of evolution and of genetics and four handbook chapters are devoted to these topics. Macroevolution, or the evolution of new species, has been seen since Darwin as a difficult biological problem, and one that has philosophical overtones. The philosopher Karl Popper famously asserted that the core Darwinian thesis – natural selection operates to separate the best adaptations in an environment – far from being a scientific insight is simply non-scientific as it is a hollow tautology (the best adapted species means that it is the species that survives). And the whole question of creation of new species demands a definition of species, something that is harder to do than it sounds. Can such definitions be given without recourse to Aristotelian essentialism? Leaving aside the powerful religious and cultural constraints in learning evolution, there are well-documented psychological constraints to mastery of the theory. The foremost of these is deep-seated, inborn, teleological mental outlooks that we all have; the animal and even vegetable world are understood as intentional and goal-driven. This is a basic Aristotelianism that is close to the surface in Lamarckian accounts of evolution and on the surface of many cultures' understanding of the natural world. This is something against which Darwin struggled, and it is inside the heads of all students. The two Evolution chapters deal with, among other things, this range of questions.

One of the genetics chapters establishes that it is a very difficult subject to teach and discusses how the history of genetics is related to important philosophical issues such as reductionism, genetic determinism and the relationship between biological function and structure. The chapter documents empirical studies where HPS considerations can improve the teaching and learning of the subject. The second genetics chapter reports results on how ideas about genes and gene function are treated in

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[12] *The School Science Review*, 1964 vol. 45, p. 366. Obviously, teachers require some understanding of debates about instrumentalism, realism and positivism to appreciate Bradley's charge.

textbooks and appear in students' views; it also reports on a teaching strategy for improving students' understanding of scientific models in genetics.

HPS has contributed to the sciences of ecology, astronomy and geology. The handbook chapters on these fields of study appraise the large bodies of research that have appealed to HPS for their better teaching and better student learning. In the cosmology chapter, we are reminded that the subject differs in some respects significantly from other sciences, primarily because of its intimate association with issues of a conceptual and philosophical nature. Because cosmology in the broader sense relates to the students' world views, it provides a means for bridging the gap between the teaching of science and the teaching of humanistic subjects, and clearly philosophical matters of time, causation and creation are germane for any informed teaching and learning of the subject.

It is worth drawing attention to the inclusion of mathematics in this first section. Unfortunately, science education handbooks too often ignore research in mathematics education. In the editorial of the first number (1992) of *Science & Education*, I wrote that: 'One major division that *Science & Education* seeks to overcome is that between researchers in mathematics education and researchers in science education. Seldom, particularly in the Anglo world, do these two groups meet or read each-others' work … The history and philosophy of science and of mathematics are interwoven disciplines, they are a natural vehicle for bringing the two communities together. Many problems in science education have their origins in the quantitative side of science, and many problems in mathematics education have their origins in the supposed irrelevance of mathematical formalism' (p. 2). Science cannot be done without mathematics, and science even from the earliest ages cannot be learnt without learning relevant mathematics; so the divorce between the two research communities is unfortunate and ultimately to the detriment of teachers and learners. The seven mathematical papers in this handbook flesh out this claim and appraise aspects of the long tradition of HPM&MT scholarship.

1.4.2 Theoretical Studies

Many topics included in the Theoretical section were straightforward; they were obvious choices. Science teachers, curriculum writers, examiners and textbook authors clearly have to address larger philosophical matters about, for example, religion, multiculturalism, indigenous knowledge systems, nature of science, scientific method and inquiry, argumentation, constructivism, evolution education, postmodernism, scientific literacy and the relation of science to personal and cultural world views. And where such questions are not addressed educators frequently need to justify their failure to do so.

Issues, for instance, about teaching and assessing the nature of science have been put on national curricular and assessment tables across the world. These NOS matters are so extensive and the research so voluminous that they are addressed in three papers. The same applies to religion where religious traditions have had centuries of engagement with science and science education and so of course does atheism. Seven papers in the handbook deal with these bodies of research and debate. There are also chapters on how the HPS&ST tradition connects to the science-technology-society (STS) tradition and more recently the cultural studies tradition in education. Examination of these connections and divergences benefits from historical and philosophical elaboration.

Other theoretical topics might not be so apparent, but nevertheless they are important; they have historical and philosophical dimensions and are covered in handbook chapters. All involved in science and mathematics education need to understand then explain core features of the subject they are teaching: what scientific explanation is, what laws are, what scientific method is or is not, what proof is, what models are, how values enter or do not enter scientific investigation and decision making, how thought experiments have functioned in science and can function in classrooms and so on. Handbook contributions discuss these topics and research on how they are best taught.

Also discussed is the topic of student learning and how research on it can be illuminated by philosophy. Many, following Dewey and Piaget, have pointed out that the psychology of learning and the epistemology of what is learnt need to be better connected. One of the biggest fields in science education research over the past four decades has been conceptual change research, yet in the famous foundational 1982 article by Posner and associates, they point out that they are proposing a theory of *rational* or *reasonable* conceptual change and assuredly the promotion of rationality and reasonable thinking is at least one aim of science education. Once this is appreciated, then it is clear that historians and philosophers can fruitfully be involved with educators; investigating rationality, its shades and alternatives, is central to their disciplines.

Likewise, when cognitive scientists say that knowledge is ‘what can be retrieved from long-term memory’, philosophers can draw on the long history of epistemology to point out serious problems with this formulation: not everything remembered is knowledge, and claims are not knowledge because they are remembered; other things are involved. Since Plato established that merely true belief is not knowledge, philosophers have discussed the ‘other things’ involved. Cross-disciplinary engagement between educators, psychologists and philosophers is the way forward here. The conceptual change and Wittgenstein chapters appraise research in this field.

Narrative teaching, informal learning and the long tradition of ‘historical investigative teaching’ which is based on student ‘reproduction’ of classical experiments and engagement in the debates occasioned by these experiments – all give rise to philosophical questions and can be illuminated by historical studies. Everyone recognises that without science teaching, there would be no science, but this core reality is oft left unexamined. The chapters here on the role of textbooks in instruction, and on the attention given, and not given, to science education by historians of science examine the literature and arguments on this nexus between science and science teaching.

One of the most important elements that guided the development of the handbook, that energised *Science & Education* journal and that fostered a good deal of the century-plus of HPS&ST writing and research is an underlying conviction about what science and mathematics education should be; that is, what personal and social goals they should pursue, what kind of teaching and assessment is appropriate and what curriculum is justified. When spelt out, this amounts to an underlying philosophy of science and mathematics education. What has animated this work is a conception of *liberal* education, but such an idea needs to be elaborated and defended against alternatives. Philosophy of education is the discipline where, since Mach and Dewey, these debates have occurred; it is a discipline with which teachers need to engage. Without doubt, the most formative influence on my own teaching and educational engagements was the work of the philosophers of education Richard Peters and Israel Scheffler, with some of Peters' arguments being the 'most practical' thing I learnt in my teacher education programme at Sydney University.

Fortunately, the handbook includes a chapter detailing and appraising the fruits of this long connection of philosophy of education with practical and theoretical issues in science and mathematics education. The specific chapter, and more broadly the 34 papers in the Theoretical section, of the handbook provides evidence for the usefulness of having Philosophy or other Foundation studies included in teacher education programmes, and for researchers having them included in doctoral programmes. As has been pointed out, without such exposure or training, educators too often adopt 'slogan-like' positions in philosophy, psychology and sociology.

1.4.3 Regional Studies

Having a regional studies section in the handbook was also straightforward. HPS&ST issues and associated research have occupied teachers and educators in many countries. By detailing for selected countries and regions, these debates and research something can be gleaned about the international extent of concern about the place of history and philosophy, or nature of science, in science teaching; and the particular ways in which teachers, academics and educational administrators in different countries have responded to this concern. The USA, England and Brazil have had the longest and most public engagement with these issues and have generated the most public and scholarly argument. Other countries have had similar debates and their history is discussed here. Of particular note is the inclusion of chapters dealing with how HPS&ST questions have been addressed in three Asian countries – Japan, China and Korea – for whom modern science was, initially, an imported body of beliefs and practices. On this matter, it is worth relating that Asia is now the 'gold medalist' for *Science & Education* article downloads, edging out both North America and Europe.

The Regional chapters can minimise the extent to which the educational wheel has to be reinvented; provincial and national decision making can be informed by the successes and failures of what has occurred elsewhere. For each country, one can see debates about curriculum construction and authority, about appropriate teacher education and about appropriate assessment. These chapters are a contribution to Comparative Education, as well as to science and mathematics education. But for space and time constraints, other countries and regions could have been included; they have their own HPS&ST histories that could be told. Certainly, more individual European countries could have been included – at least France, Spain, Greece, the Nordic countries and Turkey.

1.4.4 Biographical Studies

The fourth, Biographical studies, section is of special importance to the handbook and to HPS&ST research. Current scholarship is part of a tradition that stretches back over a century, something not often enough appreciated. Too often the arguments, analyses and conceptual distinctions of important scholars of the past, which can be a source of enlightenment in the present, are neglected. Also lost is the good example of scholarship and engagement with educational issues, processes and institutions that such writers and researchers provide and that can inspire and be emulated.

In an effort to mitigate this tendency, *Science & Education* in its early volumes reproduced each year a 'Golden Oldie', a good paper that had been published 40, 50 or 60 years earlier. These included classic papers by Israel Scheffler, Robert S. Cohen, I. Bernard Cohen, John Dewey and Walter Jung. The idea was to show that a good argument or a useful conceptual distinction stands the test of time and can be fruitfully engaged with by current researchers. Newton famously remarked that he could see further because he stood upon the shoulders of giants; this is also possible in education provided we know who and what has gone before. Unfortunately, neither teacher education nor doctoral programmes do much to spread such knowledge and consequent sense of engagement in a tradition.

Consider the opening pages of a 1929 text for UK science teachers where a successful science teacher is described as one who:

> knows his own subject … is widely read in other branches of science … knows how to teach … is able to express himself lucidly … is skilful in manipulation … is resourceful both at the demonstration table and in the laboratory … is a logician to his finger-tips … is something of a philosopher … is so far an historian that he can sit down with a crowd of [students] and talk to them about the personal equations, the lives, and the work of such geniuses as Galileo, Newton, Faraday and Darwin. More than this he is an enthusiast, full of faith in his own particular work. (F. W. Westaway, *Science Teaching*, 1929, p. 3)

After 80 years of research and debate, it is a challenge to think of what else needs adding to this account. The author, Frederick W. Westaway, was a remarkable man who himself was something of a historian and philosopher with major books published in both fields; he was also a science teacher; and perhaps above all he was an HMI, a Her Majesty's Inspector for School Science. He did not live and work in an ivory tower, but was an administrator and held for decades a crucial bureaucratic position in UK education. He is all but unknown by current science education researchers. By good fortune in 1993, I stumbled over his 440-page 1929 book on the shelf of an Auckland second-hand book shop. The handbook chapter on Westaway will do something to correct his undeserved neglect.

The five chapters in this section – on Mach, Dewey, Schwab, Westaway and Holmyard – deal with the foundation figures of HPS&ST scholarship. Chapter authors were asked to explicate the view of HPS held by their subjects and how their views connected to then-extant HPS positions, indicate how this HPS understanding had connection with educational practice, describe what impact the subject's writings had at the time and provide some hindsight evaluation of the person's place in the history of science education. A demanding task, but marvellously well done here by the chapter authors.

Others who appealed to history and philosophy of science to illuminate theoretical, curricular and pedagogical issues in science and mathematics education could have been added to the section, but space constraints intervened. Among these would be at least James Conant, Arnold Arons, Martin Wagenschein, Walter Jung, Eino Kaila and Fabio Bevilacqua. Gerald Holton whose many HPS books and articles, HPS-informed physics texts and above all his long engagement in development and promotion of the Harvard Project Physics course, has a special place in the field of HPS&ST scholarship and would be added to the Biographical section if practicalities allowed. Many others had well-developed HPS&ST ideas, but less sustained educational engagements so were not considered for inclusion. These would include J. D. Bernal, Philipp Frank, Herbert Feigl and Martin Eger. In mathematics education, comparable 'classics' lists can be provided of scholars who have consciously appealed to the history and philosophy of mathematics to address theoretical, curricular and pedagogical questions. Teachers, graduate students and professors can benefit from engaging with the writing of any of the researchers named here.

1.5 Writing and Communication

The editorial for the first issue of *Science & Education* (1992) stated that the journal will: 'encourage clear and intelligible writing that is well argued and contains a minimum of jargon' (p. 8). Frederick Westaway in his 1926 book *The Writing of Clear English* and George Orwell in his 1945 essay 'Politics and the English Language' both stressed the connection between clear writing and clear thinking. Too often in education, jargon and lazy 'eduspeak' occurs; where it does, clear and useful communication, thinking and analysis are imperilled. Different chapters pick out different examples of this malady. Effort has been made to have the handbook conform to ideals of good writing and clear communication.

Acknowledgement Springer editorial staff should be thanked: Bernadette Ohmer for suggesting, encouraging and preparing the initial path for the project and Marianna Pascale and Sathiamoorthy Rajeswari for guiding it through its complex production stage. Inevitably with such a big project, one could expect tensions and disappointments, but pleasingly there have been few. Although time

consuming, my editorial duties have been personally and professionally rewarding. I have learnt much by working with the large group of contributors from many countries and many disciplines. Much is owed to these scholars, and to the large group of reviewers who diligently commented on and corrected drafts of the chapters, and to the unsung copyeditors. Hopefully, the writing and editorial labours have reinforced the importance of 'laying out the past and current state of historical and philosophical research in science and mathematics education' and have contributed usefully to graduate students and researchers who will advance the HPS&ST programme.

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Part I
Pedagogical Studies: Physics

Chapter 2
Pendulum Motion: A Case Study in How History and Philosophy Can Contribute to Science Education

Michael R. Matthews

2.1 Introduction

The pendulum has played a major role in the development of Western society, science and culture. The pendulum was central to the studies of Galileo, Huygens, Newton, Hooke and all the leading figures of the Scientific Revolution. The study and manipulation of the pendulum established many things: an accurate method of timekeeping, leading to solving the longitude problem; discovery of the conservation and collision laws; ascertainment of the value of the acceleration due to gravity *g*, showing the variation of *g* from equatorial to polar regions and hence determining the oblate shape of the earth; provided the crucial evidence for Newton's synthesis of terrestrial and celestial mechanics, showing that fundamental laws are universal in the solar system; a dynamical proof for the rotation of the earth on its axis; the equivalence of inertial and gravitational mass; an accurate measurement of the density and hence mass of the earth; and much more. The historian, Domenico Bertoloni Meli, wrote:

> Starting with Galileo, the pendulum was taking a prominent place in the study of motion and mechanics, both as a time-measuring device and as a tool for studying motion, force, gravity and collision. (Meli 2006, p. 206)

Another historian, Bertrand Hall, attested that:

> In the history of physics the pendulum plays a role of singular importance. From the early years of the seventeenth century, when Galileo announced his formulation of the laws governing pendular motion, to the early years of this century, when it was displaced by devices of superior accuracy, the pendulum was either an object of study or a means to study questions in astronomy, gravitation and mechanics. (Hall 1978, p. 441)

No surprise that James Gleick nominated that 'the pendulum is the emblem of classical mechanics' (Gleick 1987, p. 39).

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Unfortunately, the centrality and importance of the pendulum for the development of modern science is not reflected in textbooks and school curricula where it appears as an 'exceedingly arid' subject and is mostly, even in the best classes, dismissed with well-remembered formulae [$T = 2\pi\sqrt{l/g}$] and some routine mathematical exercises and maybe some practical classes. This represents a missed opportunity for enriched physics teaching and for cultivating wider appreciation of the nature of science and its contribution to society and culture. Also missed is the opportunity to give students the sense of participation in the scientific tradition of procedures, experiments, theoretical debate and understanding that has been forged by creative and diligent thinkers, and that with good reason many have considered as the very model for intelligent investigation of the natural and social worlds.

2.2 Galileo's Pendulum Analysis

Galileo in his final work, *The Two New Sciences*, written during the period of house arrest after the trial that, for many, marked the beginning of the Modern Age, wrote:

> We come now to the other questions, relating to pendulums, a subject which may appear to many exceedingly arid, especially to those philosophers who are continually occupied with the more profound questions of nature. Nevertheless, the problem is one which I do not scorn. I am encouraged by the example of Aristotle whom I admire especially because he did not fail to discuss every subject which he thought in any degree worthy of consideration. (Galileo 1638/1954, pp. 94–95)

Galileo's comment that pendulum investigations appear 'exceedingly arid' has been echoed by science students over the following 400 years. The pendulum is regularly voted the 'most boring subject' in physics. But this need not be so: pendulum studies and investigations that are informed by the history and philosophy of the subject matter can be deeply engaging and can introduce to students the wide vista of interplay between science, technology, society, philosophy, mathematics and culture.

While the youthful Galileo was briefly a medical student at Pisa, he utilised the pendulum to make a simple diagnostic instrument for measuring pulse beats. This was the *pulsilogium*. Medical practitioners in Galileo's day realised that pulse rate was of great significance, but there was no objective, let alone accurate, measurement of pulse beat. Galileo's answer to the problem was ingenious and simple: he suspended a lead weight on a short length of string, mounted the string on a scaled board, set the pendulum in motion, and then moved his finger down the board from the point of suspension (thus effectively shortening the pendulum) until the pendulum oscillated in time with the patient's pulse. As the period of oscillation depended only on the length of the string, and not on the amplitude of swing, or the weight of the bob, the length of string provided an objective and repeatable measure of pulse speed that could be communicated between doctors and patients, and kept as a record.

The *pulsilogium* provides a useful epistemological lesson. Initially, something subjective, the pulse, was used to measure the passage of time – occurrences, especially in music, were spoken of as taking so many pulse-beats. With Galileo's *pulsilogium*, this subjective measure itself becomes subject to an external, objective, public measure – the length of the *pulsilogium*'s string. This was a small step in the direction of objective and precise measurement upon which scientific advance in the seventeenth and subsequent centuries would depend.[1]

After three decades of work, Galileo's well-known pendulum claims were the following:

LAW OF WEIGHT INDEPENDENCE: period is independent of weight
LAW OF AMPLITUDE INDEPENDENCE: period is independent of amplitude
LAW OF LENGTH: period varies directly as length; specifically the square root of length
LAW OF ISOCHRONY: for any pendulum, all swings take the same time; pendulum motion is isochronous;

After his appointment to a lectureship in mathematics at the University of Pisa in 1588, Galileo quickly became immersed in the mathematics and mechanics of the 'Superhuman Archimedes', whom he never mentions 'without a feeling of awe' (Galileo 1590/1960, p. 67). Galileo's major Pisan work is his *On Motion* (1590/1960). In it he deals with the full range of problems being discussed among natural philosophers – free-fall, motion on balances, motion on inclined planes and circular motions. In these discussions, the physical circumstances are depicted geometrically, and mathematical reasoning is used to establish various conclusions in physics: Galileo here begins the mathematising of physics. Galileo's genius was to see that all of the above motions could be dealt with in one geometrical construction. That is, motions which appeared so different in the world could all be depicted and dealt with mathematically in a common manner.[2]

Galileo develops this line of analysis in an unpublished work, *On Mechanics* (Galileo 1600/1960), a work that followed in the decade after his *On Motion*.[3] It is in *On Mechanics* that the pendulum situation which is implicit in the 1590 construction is made explicit. He deals with all the standard machines – the screw, plane, lever, pulley – and makes the very un-Aristotelian theoretical claim that:

> … heavy bodies, all external and adventitious impediments being removed, can be moved in the plane of the horizon by any minimum force. (Galileo 1600/1960, p. 171)

This is un-Aristotelian because the core of Aristotle's philosophy is that physics is to deal with the world as it is, not with an idealised or mathematical world where,

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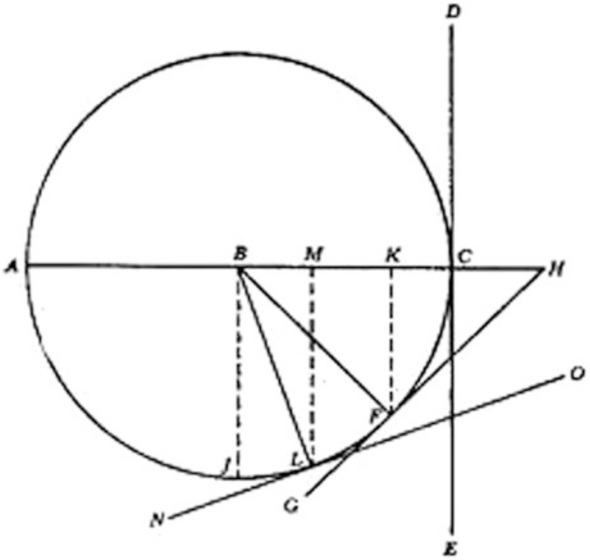
[1] Making a *pulsilogium* is a simple and rewarding class exercise. The basic lesson of science, the move from subjective experience to objective measurement, can be well illustrated.

[2] This will be a recurrent theme in the history of pendulum-related science where it is seen that many different mechanical, biological and chemical processes will manifest the mathematical formulae for Simple Harmonic Motion.

[3] Maurice Clavelin provided the foundational analysis of Galileo's early mechanics, including *De Motu* and *Le Mecaniche* in his *The Natural Philosophy of Galileo* (Clavelin 1974, Chap. 3).

contra-reality, all external and adventitious impediments are removed. For Aristotelian scientists, this is fantasy land. Nevertheless this claim of Galileo's puts him on the track towards a doctrine of circular inertia. He says that Pappus of Alexandria 'missed the mark' in his discussion of forces on bodies, because he made the assumption that 'a weight would have to be moved in a horizontal plane by a given force' (Galileo 1600/1960, p. 172). Galileo says that this assumption is false 'because no sensible force is required (neglecting accidental impediments which are not considered by the theoretician)' (Galileo 1600/1960, p. 172). He uses the following construction, and argument, to make his point, and in so doing sets up the situation that enables him to analyse pendulum motion in terms of circular motion and motion along chords of a circle.

This is a most fruitful construction. It will allow Galileo to analyse pendulum motion as motion in a circular rim and as motion on a suspended string. By considering initial, infintisimal, motions, he is able to consider pendulum motion as a series of tangential motions down inclined planes. Two years later, he will write an important letter to his patron Guidobaldo del Monte about these propositions.



Galileo's 1600 composite diagram of lever, inclined plane, vertical fall and pendulum

In his later work, Galileo expresses these pendulum claims as follows. In the First Day of his 1638 *Discorsi* Galileo expresses his law of weight independence as:

> Accordingly I took two balls, one of lead and one of cork, the former more than a hundred times heavier than the latter, and suspended them by means of two equal fine threads, each four or five cubits long. Pulling each ball aside from the perpendicular, I let them go at the same instant, and they, falling along the circumferences of circles having these equal strings for semi-diameters, passed beyond the perpendicular and returned along the same path. This free vibration repeated a hundred times showed clearly that the heavy body maintains so nearly the period of the light body that neither in a hundred swings nor even in a thousand will the former anticipate the latter by as much as a single moment, so perfectly do they keep step. (Galileo 1638/1954, p. 84)

In the Fourth Day of the 1633 *Dialogue*, Galileo states his law of amplitude independence, saying:

> … truly remarkable … that the same pendulum makes its oscillations with the same frequency, or very little different – almost imperceptibly – whether these are made through large arcs or very small ones along a given circumference. I mean that if we remove the pendulum from the perpendicular just one, two, or three degrees, or on the other hand seventy degrees or eighty degrees, or even up to a whole quadrant, it will make its vibrations when it is set free with the same frequency in either case. (Galileo 1633/1953, p. 450)

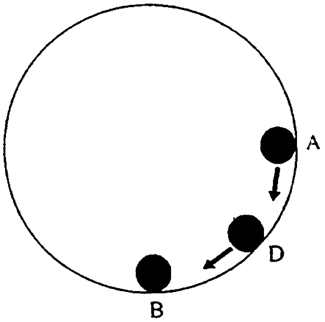
In the First Day of his 1638 *Discourse*, Galileo states his law of length when, in discussing the tuning of musical instruments, saying:

> As to the times of vibration of bodies suspended by threads of different lengths, they bear to each other the same proportion as the square roots of the lengths of the thread; or one might say the lengths are to each other as the squares of the times; so that if one wishes to make the vibration-time of one pendulum twice that of another, he must make its suspension four times as long. In like manner, if one pendulum has a suspension nine times as long as another, this second pendulum will execute three vibrations during each one of the first; from which it follows that the lengths of the suspending cords bear to each other the [inverse] ratio of the squares of the number of vibrations performed in the same time. (Galileo 1638/1954, p. 96)

Isochrony is of the greatest importance for the subsequent scientific and social utilisation of the pendulum. In the late fifteenth century, the great observer Leonardo da Vinci extensively examined, manipulated and drew pendula, but as one commentator remarks, 'He failed, however, to recognize the fundamental properties of the pendulum, the isochronism of its oscillation, and the rules governing its period' (Bedini 1991, p. 5).[4]

In the Fourth Day of the 1633 *Dialogue*, Galileo approaches his law of isochrony by saying

Take an arc made of a very smooth and polished kjconcave hoop bending along the curvature of the circumference *ADB* [Fig.6], so that a well-rounded and smooth ball can run freely in it (the rim of a sieve is well suited for this experiment). Now I say that wherever you place the ball, whether near to or far from the ultimate limit *B* . . . and let it go, it will arrive at the point *B* in equal times . . . a truly remarkable phenomenon. (Galileo 1633/1953, p. 451)



In the First Day of the 1638 *Discorsi*, Galileo writes of his law of isochrony that:

> But observe this: having pulled aside the pendulum of lead, say through an arc of fifty degrees, and set it free, it swings beyond the perpendicular almost fifty degrees, thus describing an arc of nearly one hundred degrees; on the return swing it describes a little

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[4] So not surprising that children do not just 'see' these properties. For medieval and scholastic treatments of the pendulum see Hall (1978).

> smaller arc; and after a large number of such vibrations it finally comes to rest. Each vibration, whether of ninety, fifty, twenty, ten or four degrees occupies the same time: accordingly the speed of the moving body keeps diminishing since in equal intervals of time, it traverses arcs which grow smaller and smaller. … Precisely the same thing happens with the pendulum of cork. (Galileo 1638/1954, p. 84)

In the Third Day of the *Discorsi*, he uses his law of chords to move towards a demonstration of isochrony:

> If from the highest or lowest point in a vertical circle there be drawn any inclined planes meeting the circumference the times of descent along these chords are equal to each other. (Galileo 1638/1954, pp. 188–189)

The circle on which these chords are drawn represents the path of a pendulum whose pivot is the circle's centre. Equality of time for movement on arcs will give him his sought-for isochrony proof.

Although now routine and repeated in textbooks and 'replicated' in school practical classes, these claims when made were, with good reason, very contentious and disputed. Much about science and the nature of science can be learned from the disputes.

2.3 Galileo's Methodological Innovation

The seventeenth century's analysis of pendulum motion is a particularly apt window through which to view the methodological heart of the scientific revolution. Thomas Kuhn in his *Structure of Scientific Revolutions* used Galileo's account of the pendulum to mark the epistemological transformation from the old to the new science. Kuhn wrote:

> Since remote antiquity most people have seen one or another heavy body swinging back and forth on a string or chain until it finally comes to rest. To the Aristotelians, who believed that a heavy body is moved by its own nature from a higher position to a state of natural rest at a lower one, the swinging body was simply falling with difficulty. …Galileo, on the other hand, looking at the swinging body, saw a pendulum, a body that almost succeeded in repeating the same motion over and over again ad infinitum. And having seen that much, Galileo observed other properties of the pendulum as well and constructed many of the most significant and original parts of his new dynamics around them. (Kuhn 1970, pp. 118–119)

The debate between the Aristotelian Guidobaldo del Monte (Galileo's own patron) and Galileo over the latter's pendular claims represents, in microcosm, the larger methodological struggle between Aristotelianism and the new science. This struggle is about the legitimacy of idealisation in science, and the utilisation of mathematics in the construction and interpretation of experiments (Matthews 2004; Nola 2004). All students through to the present day are in the position of da Vinci and del Monte. Without methodological assistance they do not see what Galileo 'saw'.[5]

Del Monte was a prominent mathematician, engineer and patron of Galileo (Matthews 2000, pp. 100–108; Meli 1992; Renn et al. 2000). In a 1580 letter to Giacomo Contarini, del Monte writes:

> Briefly speaking about these things you have to know that before I have written anything about mechanics I have never (in order to avoid errors) wanted to determine anything, be it as little as it may, if I have not first seen by an effect that the experience confronts itself precisely with the demonstration, and of any little thing I have made its experiment. (Renn et al. 2000, p. 339)

This then is the methodological basis for del Monte's criticism of Galileo's mathematical treatment of pendulum motion. It echoes Aristotle's empiricism: his view that 'if we cannot believe our eyes, what can we believe?' The crucial surviving document in the exchange between Galileo and his patron is a 29th November 1602 letter where Galileo writes of his discovery of the isochrony of the pendulum and conveys his mathematical proofs of the proposition.[6]

The long letter is a milestone in the history of scientific methodology. Galileo writes:

> The experiment you [del Monte] tell me you made in the [rim of a vertical] sieve may be very inconclusive, perhaps by reason of the surface not being perfectly circular, and again because in a single passage one cannot well observe the precise beginning of motion. But if you will take the same concave surface and let ball B go freely from a great distance, as at point B, it will go through a large distance at the beginning of its oscillations and a small one at the end of these, yet it will not on that account make the latter more frequently than the former. Then as to its appearing unreasonable that given a quadrant 100 miles long, one of two equal moveables might traverse the whole and [in the same time] another but a single span, I say that it is true that this contains something of the wonderful (Drake 1978, p. 69)

Thus in 1602, Galileo claimed two things about motion on chords within a circle:

1. That in a circle, the time of descent of a body free-falling along all chords terminating at the nadir, is the same regardless of the length of the chord.
2. In the same circle, the time of descent along a chord is longer than along its composite chords, even though the direct route is shorter than the composite route.

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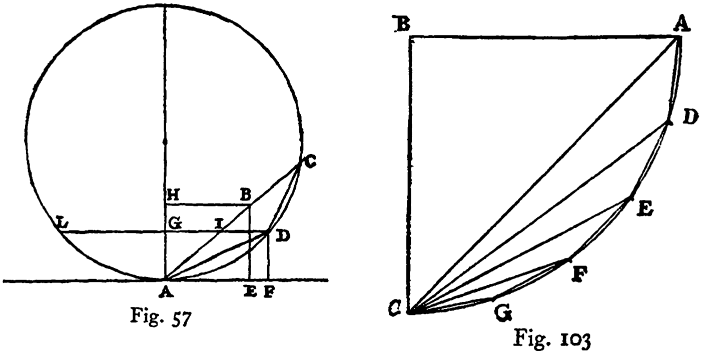
[5] Importantly, Galileo literally saw what da Vinci, del Monte and everyone else saw; what was in front of his eyes was the same as was in front of everyone else's; what was behind his eyes was the difference. He constructed a different model of the pendulum phenomenon. On this see Giere (1988, pp. 68–80, 1994)

[6] The letter was written in October 1602 (*Opere*, Edizione Nazionale, Florence 1934, vol. 10, pp. 97–100), and a translation has been provided by Stillman Drake (Drake 1978, pp. 69–71) and it is also translated in Renn et al. (1998, pp. 104–106). Ronald Naylor (1980, pp. 367–371) and W.C. Humphreys (Humphreys 1967, pp. 232–234) discuss the letter in the context of Galileo's work on the law of fall.



Galileo's geometrical constructions for his law of chords

This gets him tantalisingly close to a claim about motion along the *arcs* of the circle, the pendulum case, but not quite there. He is not prepared to make the leap, saying 'But I cannot manage to demonstrate that arcs SIA and IA are passed in equal times, which is what I am seeking'.[7] Galileo 'sees' that they are passed in equal times; he has empirical proof – if one can take hypothetical behaviour in ideal situations as empirical proof, but he lacks a 'demonstration'. This is something that he believes only mathematics can provide. Galileo needed and sought certainty in his physics as this was required for his endorsement of the Copernican view of the solar system; biblical heliocentrism could not be overturned for merely 'probable' or 'possible' science, only for demonstrable science.

The empirical problems were examples where the world did not 'correspond punctually' to the events demonstrated mathematically by Galileo. In his more candid moments, Galileo acknowledged that events do not always correspond to his theory; that the material world and his so-called 'world on paper', the theoretical world, did not correspond. Immediately after mathematically establishing his famous law of parabolic motion of projectiles, he remarks that:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola. (Galileo 1638/1954, p. 251)

One can imagine the reaction of del Monte and other hardworking Aristotelian natural philosophers and mechanicians when presented with such a qualification. When baldly stated, it confounded the basic Aristotelian and empiricist objective of science, namely to tell us about the world in which we live. Consider, for instance, the surprise of Giovanni Renieri, a gunner who attempted to apply Galileo's theory to his craft, who, when he complained in 1647 to Torricelli that his guns did not behave according to Galileo's predictions, was told by Torricelli that 'his teacher

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[7] On Galileo's geometrical constructions of pendula movement and his physical interpretations of them, see especially Machamer and Hepburn (2004).

spoke the language of geometry and was not bound by any empirical result' (Segre 1991, p. 43). Not surprisingly, del Monte said that Galileo was a great mathematician, but a hopeless physicist. His complaint was the methodological kernel of the scientific revolution in which abstraction, idealisation and mathematical analysis typified the New Science and separated it from the old science.[8]

2.4 Galileo, Experimentation and Measurement

It should not be inferred from the foregoing that Galileo was indifferent to experimental evidence. He was a most careful experimenter. His insight was to have a mathematical model of motion and then to compare real motions with this model; his 'world on paper' preceded his 'real world'. This of course was the method employed by astronomers since before Plato's time. The philosophically interesting point is what adjustments, if any and for what reasons, one makes to the mathematical model in the light of experimental results. How much does reason and how much does measurement contribute to theory development?

Galileo, as with other natural philosophers since Aristotle, was interested in understanding free fall, the most obvious terrestrial 'natural' motion. Thus, in Day Three of his *New Sciences*, Salvati (Galileo's alter ego) says: 'thus we may picture to our mind a motion as uniformly and continuously accelerated when, during any equal intervals of time whatever, equal increments of speed are given to it.' (Galileo 1638/1954, p. 161). Sagredo, the supposedly impartial bystander to the discussion, then says: 'I may nevertheless without offense be allowed to doubt whether such a definition as the above, established in an abstract manner, corresponds to and describes that kind of accelerated motion which we meet in nature in the case of freely falling bodies.' (Galileo 1638/1954, p. 162). As has often been pointed out, Galileo was interested in the 'how' of such natural motions, as well as the 'why' questions which preoccupied the Aristotelian tradition. But free fall was too fast for direct investigation and measurement, so Galileo turned to two motions that embody free fall, but in which the motion can be more easily manipulated and investigated: motion on an inclined plane and pendulum motion.

In Galileo's justly famous inclined plane experiment, he noticed initially by chanting that the distances travelled along the plane in equal time (chant) intervals were (taking the first distance to be one unit) 1, 3, 5, 7, 9, 11, etc. He then saw that the sums of these distances (total distance travelled – 1, 4, 9, 16, 25, 36) were in the proportion to the squares of the times elapsed. He proceeded to replace these chant-based, hence fixed, time-interval measurements with his ingenuous water-weighing measure of time.[9]

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[8] Some especially insightful discussions of Galileo's methodological revolution are McMullin (1978, 1990), Machamer (1998), and Mittelstrass (1972).

[9] Discussions of Galileo's inclined plane investigations are in Costabel (1975), Humphreys (1967), and Palmieri (2011).

In 1604, he tried to time accurately pendulum swings of different amplitudes using his weight of flowing water method. He took a 1740 *punto* (1.635 m) pendulum and let it swing to a vertical board from 90° and from 10°, while taking his finger off the outflow (when releasing the pendulum) and then putting it on the outflow tube of the water bowl (when the pendulum struck the board). For the full quadrant of fall he got 1,043 grains (2.17 oz) of water, for the small amplitude he got 945 grains (1.96 oz). The difference in time (9.4 %) for large and small amplitude swings is very close to the 10 % that can now be calculated for this particular length (Drake 1990, p. 22). Galileo was meticulous about his experimental results: in this case it was his interpretation that was flawed. He attributed the difference in time to *impediments*, not realising that it was the *circular* arc that was the fundamental disturbing cause. Huygens would discover this geometrically, and substitute the *cycloidal* curve for his isochronic pendulum.

One most important measurement that Galileo performed in these early years (1600–1604) was the ratio of the distance fallen from rest to the length of a pendulum whose period was the time of fall of the body. A pendulum was held out from a vertical board and released simultaneously with the dropping of a weight. He adjusted the pendulum length until the 'thud' of the pendulum hitting the wall coincided with the 'thud' of the weight hitting the floor. If t is the time from release to 'thud', then $4t$ will be the period of the pendulum (from release to vertical is one quarter of its period). This ratio is a constant for all heights of fall, and we now know it is the same at all places on earth and even on the moon; it is equal to $\pi^2/8$.

Galileo measured the time of free fall through a given length to the time of the swing of a pendulum of the same length from release to a vertical board (one quarter of its period, T). He let a ball drop 2000 *punto* (1.88 m) and timed its fall using his weight of water method (850 grains). He then took a 2000 *punto* pendulum and timed its quarter-oscillation (942 grains). The ratio of the two times was 1.108. And it is a constant for all lengths of fall. That is, for all heights, the time of fall compared to the time for a quarter oscillation of a pendulum whose length is equal to the particular height, is constant. Using modern methods, we can calculate this ratio to be equal to $\pi/2\sqrt{2}$, or 1.1107. Galileo's result of 1.108, by weighing water released during the fall on a beam balance, indicates how careful Galileo was in his experiments and measurements.[10]

2.5 Contemporary Reproductions of Galileo's Experiments

Beginning with his first biographer Vicenzio Viviani (1622–1703), through the work of Mach in the late nineteenth century, and up to Stillman Drake's compendious studies this century, Galileo has been depicted as a patient experimentalist who examined nature rather than books about nature, as Aristotelians were supposedly

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[10] Stillman Drake discusses these measurements in his *Galileo: Pioneer Scientist* (Drake 1990, pp. 23–25). So also does James MacLachlan in his *Galileo Galilei* (MacLachlan 1997, pp. 114–117).

doing. This empiricist interpretation has been the dominant tradition in Galilean historiography. Alexandre Koyré's rationalist, intellectualist, neo-Platonic interpretation of Galileo burst like a thunder-clap over this tradition (Koyré 1943, 1953, 1960). Koyré wrote of his work that:

> I have tried to describe and justify Galileo's use of the method of imaginary experiment concurrently with, and even in preference to, real experiment. In fact, it is an extremely fruitful method which incarnates, as it were, the demands of theory in imaginary objects, thereby allowing the former to be put in concrete form, and enables us to understand tangible reality as a deviation from the perfect model which it provides. (Koyré 1960, p. 82)

Against this contested historiographical background, it is also not surprising that scholars have scrutinised Galileo's pendulum experiments and have endeavoured to replicate them[11] (Ariotti 1968, 1972; MacLachlan 1976; Naylor 1974, 1976; Settle 1961, 1967). Concerning Galileo's claims for weight independence, Ronald Naylor, for instance, found that:

> Using two 76 inch pendulums, one having a brass bob, the other cork, both swinging initially through a total arc of 30°, the brass bob was seen to lead the cork by one quarter of an oscillation after only twenty-five completed swings. (Naylor 1974, p. 33)

Of the claims about amplitude independence, James MacLachlan wrote:

> Now, if anyone swings two equal pendulums through such unequal arcs [Galileo's 80° and 5°] it is easy for him to observe that the more widely swinging one takes a longer time to complete the first oscillation, and after a few more it will have fallen considerably behind the other. (MacLachlan 1976, p. 178)

Indeed the difference in period between a 90° and a 3° swing is 18 %. On the mass independence claims, MacLachlan writes:

> As for Galileo's remark that they [cork and lead balls] would not differ even in a thousand oscillations, I have found that a cork ball 10 cm. in diameter is needed just to continue oscillating 500 times. However, for the lead to be 100 times heavier than that, it would have to be more than 10 cm. in diameter, and it would make even fewer oscillations (perhaps only 93) in the time that the cork bob made a hundred. (MacLachlan 1976, p. 181)

The discrepant results of Naylor, MacLachlan and others, do not mean that Galileo's work was just 'imaginary' as Koyré suggests. Undoubtedly these experiments were conducted, but equally undoubtedly the results were 'embellished'. Ronald Naylor provides a reasonable summary of the historical evidence:

> This paper suggests that while Galileo did undoubtedly devise and use experiments similar to those described in the *Discorsi*, it seems evident that in publication he idealised and simplified the results of these researches. Thus some experimental accounts in the *Discorsi* appear to contain the essential distillate of many experiments rather than the description of any actual experiment. Ultimately, the idealised versions of the experiments seem to fuse with Galileo's theoretical model. Even so, it seems likely that at times Galileo was just as capable of providing a totally imaginary experiment in order to support his case. (Naylor 1974, p. 25)

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[11] See Ariotti (1968, 1972), MacLachlan (1976), Naylor (1974, 1976), Palmieri (2009), and Settle (1961, 1967).

Ignoring discrepant data and embellishing results is a methodological two-edged sword: it allows the experimenter to keep their eyes on the main game, but sometimes the discrepant, or outlying, results are not the product of 'accidents' and 'impediments' (Galileo's terminology), but of basic mechanisms in the world. This was the case with Galileo's continued commitment to the circle being the isochronous curve. There is an epistemological lesson to be learnt here about how experimental results relate to theoretical commitments. That is, we need, in the beginning, to distinguish the *theorised* objects of science, and their properties, from the *material* objects of the world, and their behaviour (Matthews 2000, Chap. 10), or our models of physical processes and the processes themselves (Giere 1988, Chap. 3). This distinction has important implications for pedagogical programmes of Discovery Learning, Experiential Learning and Radical Constructivism. The worst of these programmes *confine* students to their experiential world.

2.6 The Pendulum and Timekeeping

The pendulum played more than a scientific role in the formation of the modern world. The pendulum was central to the horological revolution that was intimately tied to the scientific revolution. Huygens in 1673, following Galileo's epochal analysis of pendulum motion, utilised the pendulum in clockwork and so provided the world's first accurate measure of time (Yoder 1988). The accuracy of mechanical clocks went, in the space of a couple of decades, from plus or minus half-an-hour per day to a few seconds per day.[12] This quantum increase in accuracy of timing enabled hitherto unimagined degrees of precision measurement in mechanics, navigation and astronomy. It ushered in the world of precision characteristic of the scientific revolution (Wise 1995). Time could then confidently be expressed as an independent variable in the investigation of nature.

Christiaan Huygens (1629–1695) refined Galileo's pendulum laws and was the first to use these refined laws in creating a pendulum clock. Huygens stands out among the great scientific minds of the seventeenth century who addressed themselves to the improvement of time measurement and the solution of the longitude problem. Huygens possessed both manual and intellectual skills of the highest order. He was the son of a well-connected and wealthy Dutch diplomat, who, with good reason, called his son *mon Archimède.* Upon Huygens death, the great Leibniz wrote: 'The loss of the illustrious Monsieur Huygens is inestimable; few people knew him as well as I; in my opinion he equalled the reputation of Galileo and Descartes and aided theirs because he surpassed the discoveries that they made; in a word, he was one of the premier ornaments of our time' (Yoder 1991, p. 1). Given

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[12] Among many excellent books on the history of timekeeping, see Barnett (1998), Landes (1983), and van Rossum (1996).

that the 'times' contained Galileo, Descartes, Pascal, Boyle, Newton as well as Leibniz himself, this was no small praise.

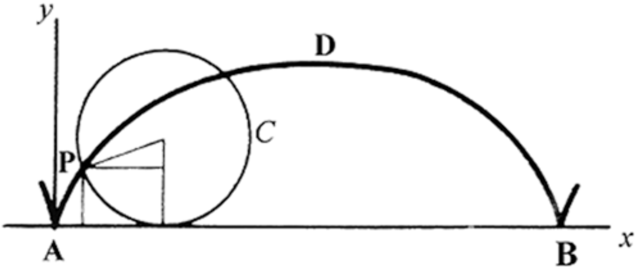
There was an element of metaphysics in Galileo's adherence to the circle as the tautochrone or path of isochronous motion. The same conviction perhaps that lead him to discuss and defend Copernicus's theory of *circular* planetary orbits, despite Kepler's *elliptical* refinement of Copernicus's views being published in 1619, 14 years before Galileo's great *Dialogue*, and Galileo having a copy of the work in his library. The same conviction perhaps led Galileo to the doctrine of *circular* inertia.[13]

Huygens modified Galileo's analysis by showing, mathematically, that it was movement on the cycloid, not the circle that was isochronous. He provides the following account of this discovery:

> We have discovered a line whose curvature is marvellously and quite rationally suited to give the required equality to the pendulum. . . . This line is the path traced out in air by a nail which is fixed to the circumference of a rotating wheel which revolves continuously. The geometers of the present age have called this line a cycloid and have carefully investigated its many other properties. Of interest to us is what we have called the power of this line to measure time, which we found not by expecting this but only by following in the footsteps of geometry. (Huygens 1673/1986, p. 11)

The cycloid is the curve described by a point P rigidly attached to a circle C that rolls, without sliding, on a fixed line AB. The full arc ABD has a length equal to 8r (r = the radius of the generating circle). A heavy point which travels along an arc of cycloid placed in a vertical position with the concavity pointing upwards will always take the same amount of time to reach the lowest point, independent of the point from which it was released.

A cycloid generated by a moving circle



Having shown mathematically that the cycloid was isochronous, Huygens then devised a simple way of making a suspended pendulum swing in a cycloidal path – he made two metal cycloidal cheeks and caused the pendulum to swing between them. Huygens first pendulum clock was accurate to one minute per day; working with the best clockmakers, he soon made clocks accurate to one second per day.

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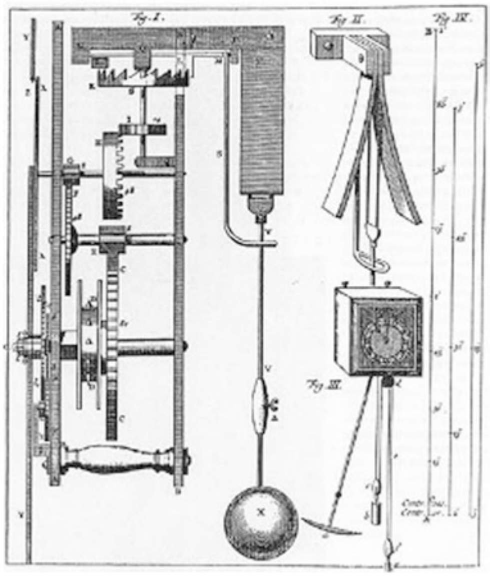
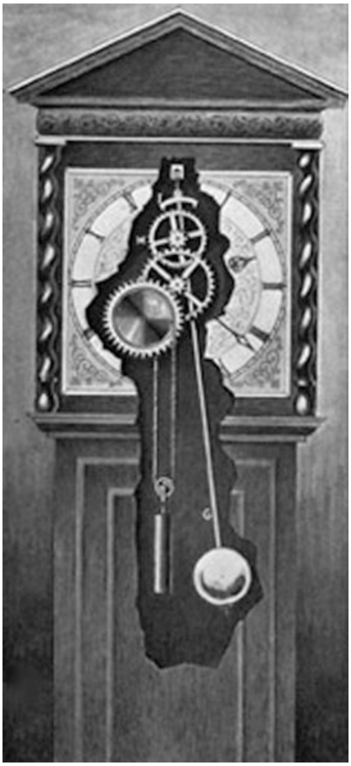
[13] Alexandre Koyré (Koyré 1943) and Edwin Burtt (Burtt 1932, pp. 61–95) regarded this metaphysical conviction as evidence of Galileo's Platonism.



Huygens' own drawings for a clock, showing the cycloidal cheeks constraining the pendulum



Cut-away pendulum clock, the slowly falling weight provided small impulses to the pendulum to maintain its motion

After showing that the period of a simple pendulum varied as the square root of its length, Huygens then derived the familiar equation:

$$T = 2\pi\sqrt{l / g}$$

The time of one small oscillation is related to the time of perpendicular fall from half the height of the pendulum as the circumference of a circle is related to its diameter [π] (Huygens 1673/1986, p.171).

2.7 The Pendulum in Newton's Mechanics

The pendulum played a comparable role in Newton's work to what it had for Galileo and Huygens. Newton used the pendulum to determine the gravitational constant **g**, to improve timekeeping, to disprove the existence of the mechanical philosophers' aether presumption, to show the proportionality of mass to weight, to determine the coefficient of elasticity of bodies, to investigate the laws of impact and to determine the speed of sound. Richard Westfall, a Newtonian scholar of great distinction, wrote: “the pendulum became the most important instrument of seventeenth-century science … Without it the seventeenth century could not have begot the world of precision” (Westfall 1990, p. 67). Concerning the pendulum’s role in Newton’s science, Westfall has said that “It is not too much to assert that without the pendulum there would have been no *Principia*” (Westfall 1990, p. 82).

2.7.1 The Demonstration of Newton’s Laws

Three properties made the pendulum an ideal vehicle for the demonstration of Newton’s laws and the investigation of collisions: pendulums of the same length reach their nadir at the same time irrespective of where they are released; they reach their nadir simultaneously regardless of their mass; and their velocity at the nadir is proportional to the length of the chord joining the nadir to the point of release. Additionally, the paths of the colliding bodies could be constrained. Newton sets up pendulum collision experiments to demonstrate his laws of motion and to explicate is nascent conservation law. He concludes one demonstration by writing:

> By the meeting and collision of bodies, the quantity of motion, obtained from the sum of the motions directed towards the same way, or from the difference of those that were directed towards contrary ways, was never changed. … (Newton 1729/1934, pp. 22–24)

Newton does not label this the conservation of momentum. He speaks ill-definedly of conservation of ‘motion’, but it is modern momentum, *mv*, a vector quality, that he is describing. In current terminology, his conclusion is given by the formula:

$$\mathrm{m_1u_1 + m_2u_2 = m_1v_2 + m_2v_2}$$

The pendulum has here made a significant contribution to the foundation of classical mechanics. The law of conservation of momentum was true for both elastic (where there is no energy absorbed in the collision itself) and inelastic collisions (where energy is absorbed). For instance, if the above pendulums were made of putty, then when they collided, they would deform and simply come to a halt, there would be no motion after the collision. In this situation one could hardly talk of conservation of ‘motion’ – although, Decartes, for instance, resolutely maintained that the quantity *mv* was the basic measure of ‘motion’, and *mv* was the basic entity that was conserved in the world.

Newton’s third law, ‘action is equal to reaction’, was demonstrated by Newton using two long (3–4 m) pendula and having them collide. He used a result of Galileo (that the speed of a pendulum at its lowest point is proportional to the chord of its arc) and applied it to the collision by comparing the quantities mass multiplied by chord length, before and after collision (Gauld 1998, 2004a). For centuries, Newton’s Cradle apparatus, which wonderfully manifests this conservation law, has intrigued students and citizens (Gauld 2006).

2.7.2 Unifying Terrestrial and Celestial Mechanics

The major question for Newton and natural philosophers was whether Newton's postulated *attractive force* between bodies was truly *universal*; that is, did it apply not only to bodies on earth, but also between bodies in the solar system? Aristotle, as with all ancient philosophers, made a clear distinction between the heavenly and terrestrial (sub-lunar) realms; the former being eternal, unchanging and perfect, the realm of the Gods; the latter being changeable, imperfect, and corruptible, the realm of man. It was thus 'natural' that the science of both realms would be different; and, to speak anachronistically, laws applying to the terrestrial realm would not apply to the celestial realm. This cosmic divide lasted for 2000 years.

It was the analysis of pendulum motion that rendered untenable the celestial/terrestrial distinction, and enabled the move from 'the closed world to the infinite universe' (Koyré 1957). The same laws governing the pendulum were extended to the moon, and then to the planets. The long-standing celestial/terrestrial distinction in physics was dissolved. The same laws were seen to apply in the heavens as on earth: there was just one world, a unitary cosmos.

At 22 years of age, while ensconced in Lincolnshire to avoid London's Great Plague, Newton began to speculate that the moon's orbit and an apple's fall might have a common cause (Herivel 1965, pp. 65–69). He was able to calculate that in 1 s, while travelling about 1 km in its orbit, the moon deviates from a straight-line path by about a twentieth of an inch. In the same period of time an object projected horizontally on the earth would fall about 16 feet. The ratio of the moon's 'fall' to the apple's fall is then about 1:3,700. This was very close to the ratio of the square of the apple's distance from the earth's centre (the earth's radius), to the square of the moon's distance from the earth's centre, 1:3,600. Was this a cosmic coincidence? Or did the earth's gravitational attraction apply equally to the apple and the moon?

Following the dictates of his own method, Newton then experimentally investigates whether the derived consequences are seen in reality. He defers to Huygens' experimental measurement, saying:

> And with this very force we actually find that bodies here upon earth do really descend; for a pendulum oscillating seconds in the latitude of *Paris* will be 3 *Paris* feet, and 8 lines ½ in length, as Mr *Huygens* has observed. And the space which a heavy body describes by falling in one second of time is to half the length of this pendulum as the square of the ratio of the circumference of a circle to its diameter (as Mr *Huygens* has also shown), and is therefore 15 *Paris* feet, 1 inch, 1 line $^7/_9$ And therefore the force by which the moon is retained in its orbit becomes, at the very surface of the earth, equal to the force of gravity which we observe in heavy bodies there. (Newton 1729/1934, p. 408)

Newton then draws his conclusion:

> And therefore the force by which the moon is retained in its orbit is that very same force which we commonly call gravity.

The pendulum had brought heaven down to earth.[14]

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[14] On the pendulum's role in this unification, see especially Boulos (2006).

2.8 Huygens' Proposal of an International Standard of Length

Huygens saw that in his pendulum equation $T = 2\neq \sqrt{l/g}$ he only variable was l, as π was a constant and, provided one stayed near to sea level, *g* was also constant, and mass did not figure in the equation at all. So all pendula of a given length will have the same period, whether they be in France, England, Russia, Latin America, China or Australia. Huygens was clever enough to see that the pendulum would solve not only the timekeeping and longitude problems, but an additional vexing problem, namely establishing an international length standard, and in 1673 he proposed the length of a seconds pendulum (a pendulum that beats in seconds; that is, whose period is 2 s) to be the international unit. The length of the seconds pendulum was experimentally determined by adjusting a pendulum so that it oscillated $24 \times 60 \times 60$ times in a sideral day; that is, between successive transits of a fixed star across the centre of a graduated telescope lens (the sideral day being slightly longer than a solar day).

This seems like a daunting task, but it was not so overwhelming. Huygens and others knew that the length l of a pendulum varied as the square of period or T^2. So the length of a seconds pendulum is to the length of any arbitrary pendulum as $1/T^2$. But $1/T^2$ is as $n^2/60^2$, or the square of the number of swings or beats in 3,600 seconds or one hour. As Meli observes: 'therefore, by counting the number of oscillations and the length of his pendulum, Huygens could determine the length of the seconds pendulum' (Meli 2006, p. 205).

Having an international unit of length, or even a national unit, would have been a major contribution to simplifying the chaotic state of measurement existing in science and everyday life. Within France, as in other countries, the unit of length varied from city to city, and even within cities. This was a significant problem for commerce, trade, construction, military hardware and technology; to say nothing of science. Many attempts had been made to simplify and unify the chaotic French system. One estimate is that in France alone there were 250,000 different, local, measures of length, weight and volume (Alder 1995, p. 43). And each European state had comparable confusion of abundance, as did, of course, all other nations and cultures.

In the standard formulae, it is easy to show that the length of a seconds pendulum will be one metre.

$$
\begin{aligned}
&T = 2\pi\sqrt{l/g}\\
&\text{So } T^2 = 4\pi^2 l/g\\
&\text{So } l = T^2 g/4\pi^2\\
&\text{Substitute } T = 2\text{s}\left(\text{beat is a second}\right),\ g = 9.8\text{ms}^{-2}, \pi^2 = 9.8\\
&\text{Then } l = 1\text{m}
\end{aligned}
$$

And this result can reliably be demonstrated with even the crudest one-metre pendulum, a heavy nut on a piece of string suffices: 10 complete swings will take 20 s, 20 complete swings will take 40 s. A great virtue of the seconds pendulum as the international length standard was that it was a fully ‘natural’ standard; it was something fixed by nature unlike standards based on the length of a king’s arm or foot. And of course an international length standard would provide a related volume standard and hence a mass standard when the unit volume was filled with rain water. A kilogram is the weight of one litre (1,000 cc) of water. All of this can be engagingly reproduced with classes.

It is not accidental that 200 years after Huygens, the General Conference on Weights and Measures meeting in Paris defined the standard universal metre as ‘the length of path travelled by light in vacuum during a time interval of 1/299,792,458 of a second’.[15] This seemingly bizarre and arbitrary figure is within a millimetre of Huygen’s original and entirely natural length standard, and it was so chosen precisely to replicate the length of the seconds pendulum. Unfortunately it is the former, not the latter, that students meet in the opening pages of their science texts, and so confirms their worst fears about the ‘strangeness’ of science. In the definition of standards, science gets off to a bad pedagogical start.

2.9 The Pendulum and Determining the Shape of the Earth

Huygen’s proposal depended on g being constant around the world (at least at sea level); it depended on the earth being spherical. This seemed a most reasonable assumption. Indeed to say that the earth was not regular and spherical was tantamount to casting aspersions on the Creator: surely God the Almighty would not make a misshapen earth. But in 1673, contrary to all expectation, this assumption was brought into question by the behaviour of the pendulum.

When Jean-Dominique Cassini (1625–1712) became director of the French *Académie Royale des Sciences* in 1669 he began sending expeditions into the different parts of the world to observe the longitudes of localities for the perfection of geography and navigation. The second such voyage was Jean Richer’s to Cayenne in 1672–1673 (Olmsted 1942). Cayenne was in French Guiana, at latitude approximately 5°N. It was chosen as a site for astronomical observations because equatorial observations were minimally affected by refraction of light passing through the earth’s atmosphere – the observer, the sun and the planets were all in the same plane.

The primary purpose of Richer’s voyage was to ascertain the value of solar parallax and to correct the tables of refraction used by navigators and astronomers. A secondary consideration was checking the reliability of marine pendulum clocks which were being carried for the purpose of establishing Cayenne’s exact longitude.

The voyage was spectacularly successful in its primary purposes: the obliquity of the ecliptic was determined, the timing of solstices and equinoxes was refined and, most importantly, a new and far more accurate value for the parallax of the sun was ascertained – 9.5″ of arc. But it was an unexpected consequence of Richer’s voyage

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[15] Accounts of the development of the standard metre can be found in Alder (1995, 2002), Kula (1986, Chaps. 21–23).

which destroyed Huygens' vision of a universal standard of length 'for all nations and all ages'.

Richer found that a pendulum set to swing in seconds at Paris, had to be shortened in order to swing in seconds at Cayenne, not much – 2.8 mm, about the thickness of a matchstick – but nevertheless shortened. Richer found that a Paris seconds-clock apparently lost 2½ min daily at Cayenne. And the only apparent explanation for slowing of the pendulum at the equator was that g is less at the equator than at Paris and the poles – in other words, that the earth is a 'flattened' sphere, an oblate, with the equator being further from the centre than the poles.[16]

2.10 The Testing of Scientific Theories

Richer's claim that the pendulum clock slows in equatorial regions nicely illustrates some key methodological matters about science, and about theory testing. The entrenched belief since Erastosthenes in the second century BC was that the earth was spherical (theory T), and on the assumption that gravity alone affects the period of a constant length pendulum, the observational implication was that period at Paris and the period at Cayenne of Huygens' seconds-pendulum would be the same (O). Thus T implies O:

$$T \rightarrow O$$

But Richer seemingly found that the period at Cayenne was longer (~ O). Thus, on simple, falsificationist views of theory testing such as were enunciated first by Huygens himself, and famously developed by the philosopher Karl Popper early in the twentieth century (Popper 1934/1959), we have:

$$\begin{array}{r} T \rightarrow O \\ \sim O \\ \therefore \sim T \end{array}$$

But theory testing is never so simple – a matter that was recognised by Popper, and articulated by Thomas Kuhn (1970) and Imre Lakatos (1970). In the seventeenth century, many upholders of T just denied the second premise, ~O. The astronomer Jean Picard, for instance, did not accept Richer's findings. Rather than accept the message of varying gravitation, he doubted the messenger. Similarly, Huygens did not think highly of Richer as an experimentalist.

Others saw that theories did not confront evidence on their own, there was always an 'other things being equal' assumption made in theory test; there were *ceteris paribus* clauses (C) that accompanied the theory into the experiment. These clauses

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[16] On the history of debate about the shape of the earth, see Chapin (1994), Greenberg (1995) and Heiskanen and Vening Meinesz (1958).

characteristically included statements about the reliability of the instruments, the competence of the observer, the assumed empirical state of affairs, theoretical and mathematical devices used in deriving O, and so on. Thus:

$$\begin{aligned} T + C &\rightarrow O \\ &\sim O \\ \therefore \sim T &\text{ or } \sim C \end{aligned}$$

People who maintained belief in T, reasonably said that the assumption that other things were equal was mistaken – perhaps humidity had interfered with the swings, heat had lengthened the pendulum, friction at the pivot increased in the tropics and so on. These, in principle, were legitimate concerns. But more and more evidence came in, and from other experimenters including Sir Edmund Halley, confirming Richer's observations. Thus ~ O became established as a scientific fact, to use Fleck's terminology (Fleck 1935/1979), and upholders of T, the spherical earth hypothesis, had to adjust to it. This was not easy; giving up established theories in science is never easy, especially as the alternative was to accept that the earth was oblate in shape, an ungainly shape for the Creator to have fashioned.

There were a number of obvious items in **C** that could be pointed to as the cause of the pendulum slowing:

C^1 The experimenter was incompetent.

C^2 Humidity in the tropics caused the pendulum to slow because the air was denser.

C^3 Heat in the tropics caused the pendulum to expand, hence it beat slower.

C^4 The tropical environment caused increased friction in the moving parts of the clock.

Each of these could account for the slowing, and hence preserve the truth of the spherical earth theory. But each of them was in turn ruled out by progressively better controlled and conducted experiments. Many of course would say that adjustment of the thickness of a match (3 mm) as a proportion of a metre (1,000 mm) was so minimal that it could just be attributed to experimental error, or simply ignored. And if the theory is important, then that is an understandable tendency. But for more tough-minded scientists it seemed that the long held, and religiously endorsed, theory of the spherical earth had to be rejected.

But Huygens could see a more sophisticated explanation for the lessening of g at the equator, whilst still maintaining T, the theory of a spherical earth. He argued that:

C^5 Objects at the equator rotated faster than at Paris and hence the centrifugal force at the equator was greater, this countered the centripetal force of gravity, hence diminishing the nett downwards force (gravity) at the equator, hence decreasing the speed of oscillation of the pendulum; that is, increasing its period.

This final explanation for the slowing of equatorial pendula was quite legitimate and appeared to save the theory. Many would be happy to just pick up this 'get out of jail free' card and continue to believe that the earth was spherical. Huygens did not do so. He calculated the actual centrifugal force at the equator and determined that a shortening of 1.5 mm was required to make up for the spinning earth effect.[17] But this left 1.5 mm not accounted for. This is less than the thickness of a match, yet for such a minute discrepancy Huygens and Newton were prepared to abandon the spherical earth theory and claim that the true shape of the earth was an oblate. For the new quantitative science, 'near enough' was not 'good enough', something that students can be taught to appreciate.

This episode did not escape the attention of Voltaire, a populariser of Newtonian science and a key figure in the European Enlightenment who, in 1738, wrote:

> At last in 1672, Mr Richer, in a Voyage to Cayenna, near the Line, undertaken by Order of Lewis XIV under the protection of Colbert, the Father of all Arts; Richer, I say, among many Observations, found that the Pendulum of his Clock no longer made its Vibrations so frequently as in the Latitude of Paris, and that it was absolutely necessary to shorten it by a Line, that is, eleventh Part of our Inch, and about a Quarter more.
>
> Natural Philosophy and Geometry were not then, by far, so much cultivated as at present. Who could have believed that from this Remark, so trifling in Appearance, that from the Difference of the eleventh of our Inch, or thereabouts, could have sprung the greatest of physical Truths? It was found, at first, that Gravity must needs be less under the Equator, than in the Latitude of France, since Gravity alone occasions the Vibration of a Pendulum.
>
> In Consequence of this it was discovered, that, whereas the Gravity of Bodies is by so much the less powerful, as these Bodies are farther removed from the Centre of the Earth, the Region of the Equator must absolutely be much more elevated than that of France; and so must be farther removed from the Centre; and therefore, that the Earth could not be a Sphere. (Fauvel and Gray 1987, p. 420)

He dryly commented that:

> Many Philosophers, on occasion of these Discoveries, did what Men usually do, in Points concerning which it is requisite to change their Opinion; they opposed the new-discovered Truth. (Fauvel and Gray 1987, p. 420)

Voltaire and proponents of the Enlightenment thought that the way that the Shape of the Earth debate was resolved could be emulated in other fields of hotly contested debate and disagreement – especially in politics, religion, ethics and law – and instead of doing what 'men usually do' in these fields, they would do what the natural philosophers did, namely change their opinions when contrary evidence accrued and was verified.[18]

2.11 Some Social and Cultural Impacts of Timekeeping

The advent of accurate timekeeping in the eighteenth century had enormous impact on European social and cultural life, and by extension on the rest of the globe.

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[17] For the physics and mathematics of these calculations, see Holton and Brush (2001, pp. 128–129).

[18] This is a wonderful episode in the history of science. A great story can be made, even a drama. All the elements are there: powerful and prestigious figures, 'no name' outsiders, struggles over a big issue, mathematics and serious calculations, religion, final decisions and ample opportunity to preserve the status quo. But sadly the episode is little known and hardly ever taught.

2.11.1 Solving the Longitude Problem

Accurate time measurement was long seen as the solution to the problem of longitude determination which had vexed European maritime nations in their efforts to sail beyond Europe's shores. If an accurate and reliable clock was carried on voyages from London, Lisbon, Genoa, or any other port, then by comparing its time with local noon (as determined by noting the moment of an object's shortest shadow or, more precisely, by using optical instruments to determine when the sun passes the location's north–south meridian), the longitude of any place in the journey could be ascertained. The physics was simple. The earth rotates 360° in 24 h, or 15° in one hour, or one degree each 4 min. So if at destination the clock at origin is set to 12 at noon then if at destination at noon it reads 10 am at local noon, then the destination is 30° east of origin. As latitude could already be determined, this enabled the world to be mapped. In turn, this provided a firm base on which European trade and colonisation could proceed. The chances of being lost at sea were greatly decreased. John Harrison's marine chronometer, which followed on his extensive pendulum clock constructions, solved the longitude problem.[19]

2.11.2 A Clockwork Society

The clock transformed social life and customs: patterns of daily life could be 'liberated' from natural chronology (the seasonally varying rising and setting of the sun) and subjected to artificial chronology; labour could be regulated by clockwork and, because time duration could be measured, there could be debate and struggle about the length of the working day and the wages that were due to agricultural and urban workers; timetables for stage and later train and ship transport could be enacted; the starting time for religious and cultural events could be specified; punctuality could become a virtue; and so on. The transition from 'natural' to 'artificial' hours was of great social and psychological consequence: technology, a human creation, begins to govern its creator.[20] Lewis Mumford, the social historian, has commented that

> The clock, not the steam-engine, is the key-machine of the modern industrial age. … by its essential nature it dissociated time from human events and helped create the belief in an independent world of mathematically measurable sequences: the special world of science. (Mumford 1934, pp. 14–15)

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[19] Dava Sobel has given the Longitude Problem enormous exposure (Sobel 1995). Other more detailed and wide-ranging treatments are in Andrewes (1998), Gould (1923) and Howse (1980).

[20] Many books deal with the social and cultural history of timekeeping, among them are: Cipolla (1967), Landes (1983), Macey (1980), and Rossum (1996).

2.11.3 A Clockwork Universe and Its Maker

The clock did duty in philosophy. It was a metaphor for the new mechanical world-view that was challenging the entrenched Aristotelian, organic and teleological, view of the world that has sustained so much of European intellectual and religious life. In theology, the clock was appealed to in the influential argument from design for God's existence – if the world functions regularly like a clock, as Newton and the Newtonians maintained, then there must be a cosmic clockmaker.[21]

Leibniz closes his famous 'world as clock' correspondence with the Newtonian Samuel Clark by writing:

> I maintained that the dependence of the machine of the world upon its divine author, is rather a reason why there can be no such imperfection in it; and that the work of God does not want to be set right again; that it is not liable to be disordered; and lastly, that it cannot lessen in perfection. (Alexander 1956, p. 89)

2.11.4 Foucault's Pendulum Makes Visible the Earth's Rotation

The pendulum provided the first ever visible and dynamic 'proof' of the rotation of the earth. On Newton's theory, a pendulum set swinging in a particular plane, should continue to swing indefinitely in that same plane. The only forces on the bob being the tension in the cord, and its weight directed vertically downwards. Léon Foucault – described as 'a mediocre pupil at school, [but] a natural physicist and an incomparable experimenter' (Dugas 1988, p. 380) – 'saw' that if a pendulum were placed exactly at the north pole, and suspended in such a way that the point of suspension was free to rotate (i.e. it did not constrain the pendulum's movement by applying torque), then:

> if the oscillations can continue for twenty-four hours, in this time the plane will execute a whole revolution about the vertical through the point of suspension. … at the pole, the experiment must succeed in all its purity. (Dugas 1988, p. 380)

As the pendulum is moved from the pole to the equator, Foucault easily showed that if T^1 is the time in which the plane of the pendulum rotates 360°, and T is the period of rotation of the earth, and β is the latitude where the experiment is being conducted, then:

$$T^1 = T / \sin\beta$$

From the formula, it can be seen that at the poles, $T^1 = T$ (as $\sin\beta = \sin 90° = 1$); whereas at the equator $T^1 = \propto$ (or infinity, as $\sin 0° = 0$), thus there is no rotation of the plane of oscillation at the equator.

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[21] Macey (1980), Pt. II is a nice introduction to the utilisation of the clock in eighteenth-century philosophy and theology.

On February 2, 1851, Foucault invited the French scientific community to 'come see the Earth turn, tomorrow, from three to five, at Meridian Hall of the Paris Observatory'. His eponymously named long massive pendulum provided an experimental 'proof' of the Copernican theory; something that eluded Galileo, Newton and all the other mathematical and scientific luminaries who sought it (Tobin 2003; Aczel 2003, 2004).

Until Foucault's demonstration, all astronomical observations could be fitted, with suitable adjustments such as those made by Tycho Brahe, to the stationary earth theory of the Christian tradition. The 'legitimacy' of such ad hoc adjustments in order to preserve the geocentric model of the solar system was exploited by the Catholic Church that kept the works of Copernicus and Galileo on the *Index of Prohibited Books* up until 1835 (Fantoli 1994, p. 473). To most nineteenth-century physicists, the manifest rotation of Foucault's pendulum shown in the successive knocking down of markers placed in a circle, was a dramatic proof of the earth's rotation. Around the world tens of thousands read accounts of the pendulum, and thousands attended demonstrations; scores of newspapers editorialised on the subject; cartoonists had a picnic with it (Conlin 1999).

2.12 The Pendulum in the Classroom

It has been long recognised that much of Newtonian physics could be demonstrated, and properties of the world determined, by experimental manipulation of the pendulum. The conical pendulum, for instance, representing idealised planetary circular motion with constant velocity and yet a constant force and acceleration towards the centre. In the century after Newton, the pendulum was used widely in illustrating or 'proving' the fundamentals of Newtonian science, or classical physics, as we know it. Mathematics gave a description of the pendulum's movement (the phenomenon) without causal explanation, while Newton's laws identify the dynamic factors responsible for the observed motion. This is how physics is done: first represent or model the idealised phenomenon in mathematical terms, then explain it using the best causal theory (Newburgh 2004, pp. 297–299).[22] Then progressively try to mathematically represent less and less idealised and more and more realistic versions of the phenomenon and seek to identify the secondary causes or interfering factors with this progression going hand-in-hand with refinement of experimental situations. This is the progression from the idealised simple pendulum to the damped friction-affected realistic pendulum.

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[22] The pendulum, and all physical phenomena, can be represented by different mathematical devices: geometry, Hamiltonian equations and so on. Geometry has the advantage of connecting more immediately and intuitively to the physics of the phenomena; a not inconsiderable advantage and so a step that students should pass through on their way to algebraic representation of the pendulum.

The simple pendulum became more sophisticated – conical, compound, cradle, torsion, reversible, ballistic, coupled pendula were all crafted – and thus extending the range and accuracy of classical mechanics. The pendulum was recognised as a case of Simple Harmonic Motion where the displacing force and motion are directly and inversely related, and this motion was recognised as ubiquitous in nature.

Following Galileo, Huygens and Newton, numerous famous physicists have been associated with this history: Robert Hooke, Henry Kater, Count Rumford, George Atwood, George Stokes, Roland von Eötvös, Henry Cavendish, and others. In the past century, further developments occurred with the chaotic and quantum pendula. And at every stage the intimate dependency of physics on mathematics is apparent.[23] Two physicists have commented that:

> There is a quite unexpected connection between the classical pendulum – chaotic or otherwise – and quantum mechanics when it functions on a macroscopic scale, as happens in superconductors. More specifically, the connection arises through something known as the Josephson effect. … there is an exact correspondence between the dynamics of the Josephson devices and the dynamics of the classical pendulum. (Baker and Blackburn 2005, p. 211)

The pendulum has long been part of the physics curriculum, a fact well documented in Colin Gauld's structured bibliography of nearly 300 pendulum articles that have appeared over the past 50 years in four major physics teaching journals (Gauld 2004b). Teachers have used the simple pendulum, swinging through small angles, to teach the skills of measurement and graphical techniques for deriving the relationship between dependent (in this case, period) and independent variables (length of the string). More complex types of pendulums (such as the physical, spring-mass, torsional and Wilberforce pendulums) have been used to demonstrate dramatically a wide range of physical phenomena and provide a context in which students can become acquainted with the process of mathematical modelling in science. In the classroom, pendulum motion provides a model for many everyday oscillatory phenomena such as walking and the movement of a child's swing. At the tertiary level there has been renewed interest in the pendulum to demonstrate chaotic behaviour. For these investigations, the pendulum amplitude is unrestricted and the point of suspension is vibrated at varying amplitudes and frequencies. By removing the requirement that the amplitude be small, the behaviour of the pendulum as a non-linear oscillator can clearly be seen (Weltner et al. 2004). And the pendulum has been used to facilitate students moving from classical understanding to quantum physics (Barnes et al. 2004).

The history of pendulum investigations contains almost everything required to teach the fundamentals of kinematics, dynamics and classical physics, along with scientific methodology, epistemology and process skills. Nevertheless this history is sadly under-utilised in schools; much more could be made, beginning at the

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[23] Gregory Baker and James Blackburn provide an excellent account of the role played by the pendulum in the development of physics from Galileo to superconductivity (Baker and Blackburn 2005). Randall Peters discusses largely unexplored uses of the pendulum in investigating the science of material deformation and creep (Peters 2004).

kindergarten level, of the pendulum as a device for teaching physics content, scientific methodology, relationships of science, technology, society and culture, and more broadly for teaching the nature of science. This is especially so when repeatedly curriculum documents speak of the need to teach ‘science in context’, to teach ‘the connection of science and technology’, to teach ‘the relationship of science to everyday life’, to teach ‘the big picture of science’. The pendulum allows all of these liberal educational goals to be advanced if not achieved. This contrast between the pendulum’s scientific and social importance and its educational neglect highlights an increasingly recognised deficiency in science education: There is little sense of students being introduced to and appreciating a tradition of thought. Music, Art, Literature, Philosophy and Theology students are given this sense of tradition and appreciation of the major contributors to it; science students only barely, if at all. Education does little to make more general Newton’s sense of ‘standing on the shoulders of giants’.

2.13 The Pendulum and Textbooks

Science textbooks pay very little attention to the historical, methodological and cultural dimension of pendulum motion. It is sometimes given a cameo appearance in the story of Galileo who supposedly during a church sermon observed a swaying chandelier and timed its swings with his pulse, and ‘hey presto’ there was the law of isochronic motion. This account is found in Fredrick Wolf’s physics text:

> When he [Galileo] was barely seventeen years old, he made a passive observation of a chandelier swinging like a pendulum in the church at Pisa where he grew up. He noticed that it swung in the gentle breeze coming through the half-opened church door. Bored with the sermon, he watched the chandelier carefully, then placed his fingertips on his wrist, and felt his pulse. He noticed an amazing thing. . . . Sometimes the chandelier swings widely and sometimes it hardly swings at all . . . [yet] it made the same number of swings every sixty pulse beats. (Wolf 1981, p. 33)

Wolf’s story, *sans* boredom, appears in the opening pages of the most widely used high-school physics text in the world – the Physical Science Study Committee’s *Physics* (PSSC Physical Science Study Committee 1960).

Whatever the problems with Wolf and the PSSC text might be, the Galileo story is at least presented. However, more often the pendulum appears in physics texts without any historical context; as a standard it is introduced merely as an instance of simple harmonic motion. The extent to which the pendulum has been plucked from its historical and cultural roots can be seen in the Harvard Project Physics text, an excellent and most contextual of texts where, nevertheless, the equation:

$$\mathrm{T} = 2\pi\sqrt{\mathrm{l}/\mathrm{g}}$$

is abruptly introduced for the period of the pendulum, and students are told ‘you may learn in a later physics course how to derive the formula’ (Holton et al. 1974, p. 98).

2.14 The Pendulum and Recent US Science Education Reform Proposals

It is instructive, if sobering, to look at the utilisation of the pendulum in the past three decades of intense efforts to improve US school science programmes. These efforts have involved thousands of individuals in bodies such as the American Association for the Advancement of Science, the National Research Council, the National Academy of Science, the National Academy of Engineering, the National Science Foundation; peak disciplinary bodies in physics, chemistry, biology, earth science; and all major national and state science education organisations including the National Science Teachers Association and the National Association for Research in Science Teaching.

The reform efforts have their origin in the 1983 Reagan-era Report *A Nation at Risk: An Imperative for Educational Reform* (NCEE 1983).[24] Concerning science education, the Commission recommended that:

> The teaching of science in high school should provide graduates with an introduction to: (a) the concepts, laws, and processes of the physical and biological sciences; (b) the methods of scientific inquiry and reasoning; (c) the application of scientific knowledge to everyday life; and (d) the social and environmental implications of scientific and technological development. Science courses must be revised and updated for both the college-bound and those not intending to go to college. (NCEE 1983, p. 25)

This ‘liberal’ or contextual approach to science education has been followed-through in all subsequent major US curricular reform proposals. Clearly the pendulum is tailor made to contribute to the realisation of each of the four stated goals of reformed science education. Needless to say, this opportunity has been underutilised, to put not too fine a point on it. Everyone recognises that there is a gulf between the content of curriculum documents and the content of classroom practice; but here the gulf begins in the documents themselves, between the stated ‘liberal’ objectives and the curriculum content.

2.14.1 Scope, Sequence and Coordination

The large-scale and influential curriculum proposal of the US National Science Teachers Association (NSTA) – *Scope, Sequence and Coordination* (Aldridge 1992) – highlights the pendulum to illustrate its claims for sequencing and coordination in science instruction. Yet nowhere in its discussion of the pendulum is history, philosophy or technology mentioned. That such a huge and well-funded body as NSTA could, in the early 1990s, write a national science curriculum

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[24] Gerald Holton, a member of National Commission for Excellence in Education (NCEE) that prepared the report, has provided an account of its disturbing contents that chart the ‘tide of mediocrity’ in US education, and its recommendations for turning the tide (Holton 1986).

proposal without the participation of historians or philosophers of science is a sad commentary on the gulf between the science education and the HPS communities.[25]

2.14.2 Project 2061

In 1989, the American Association for the Advancement of Science (AAAS) published its wonderfully comprehensive *Science for All Americans* report (AAAS 1989). It acknowledged that 'schools do not need to be asked to teach more and more content, but rather to focus on what is essential for scientific literacy and to teach it more effectively' (AAAS 1989, p. 4). The report saw that students need to learn about 'The Nature of Science', and hence that was the title of the report's first chapter. The report recognised the importance of learning about the interrelationship of science and mathematics, saying: 'The alliance between science and mathematics has a long history dating back many centuries. … Mathematics is the chief language of science' (AAAS 1989, p. 34). And it acknowledged that some episodes in the history of science should be appreciated because 'they are of surpassing significance to our cultural heritage' (AAAS 1989, p. 111). Among the ten such episodes it picks out is Newton's demonstration that the same laws apply to motion in the heavens and on earth' (AAAS 1989, p. 113). It provides a very rich elaboration of this episode and its scientific, philosophical and cultural impacts. Unfortunately, there is no mention of what enabled Newton to achieve this unification, namely the pendulum; had such mention been made, this 'big idea' could have been connected to something tangible in all students' experience, the place of mathematics in science could have again been underlined, and a wonderful case study in the nature of science could have been built upon.

2.14.3 The US National Standards

The underutilisation of the pendulum can be gauged from looking at the recently adopted US National Science Education Standards (NRC 1996). The *Standards* adopt the same liberal or expansive view of scientific literacy as the NCEE did in 1983 saying that it 'includes understanding the nature of science, the scientific enterprise, and the role of science in society and personal life' (NRC 1996, p. 21). The *Standards* devote two pages to the pendulum (pp. 146–147). However there is no mention of the history, philosophy, or cultural impact of pendulum motion studies; no mention of the pendulum's connection with timekeeping; no

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[25] This observation was made in 1992 by a senior NSTA official in private correspondence with the author.

mention of the longitude problem; and no mention of Foucault's pendulum. Astonishingly in the suggested assessment exercise, the obvious opportunity to connect standards of length (the metre) with standards of time (the second) is not taken. Rather, students are asked to construct a pendulum that makes six swings in 15 s. This is a largely pointless exercise, especially when they could have been asked to make one that beats in seconds and then measure its length and inquire about the coincidence between their seconds pendulum and the metre (Matthews 1998).

Depressingly the *Standards* document was reviewed in draft form by tens of thousands of teachers and educators. It is clear that if even a few of the readers had a little historical and philosophical knowledge about the pendulum, this could have transformed the treatment of the subject in the *Standards* and would have encouraged teachers to realise the liberal goals of the document through their treatment of the pendulum. This would have resulted in a much richer and more meaningful science education for US students. That this historical and philosophical knowledge is not manifest in the *Standards* indicates the amount of work that needs to be done in having science educators become more familiar with the history and philosophy of the subject they teach, and of having the US science education community more engaged with the communities of historians and philosophers of science.

2.14.4 America's Lab Report

The US National Research Council commissioned a large study on practical work in US schools which was published as *America's Lab Report: Investigations in High School Science* (NRC 2006). The book has 236 pages, seven chapters, and hundreds of references. The pendulum has three entries in the Index. On its first appearance, it is said to be regrettable that teachers simplify pendulum experiments and ignore the 'host of variables that may affect its operation' (NRC 2006, p. 117). Teachers are advised to recognise these 'impediments' such as friction and air resistance but the writers go on to say that this 'can quickly become overwhelming to the student and the instructor' (NRC 2006, p. 118). This is not very helpful. It could have been an occasion to say something about the fundamental importance of idealisation and abstraction to the very enterprise of science, of not letting the trees get in the way of seeing the forest. This was the problem identified by Thomas Kuhn in his discussion of the pendulum and faced by da Vinci; it is the heart of the debate between Galileo and his patron Guidabaldo del Monte. But the *Lab Report* says nothing about this fundamental scientific procedure much less provide some historical background to its resolution. The pendulum allows in a tangible way for students to begin seeing the effect of 'impediments' and 'accidents' (Koertge 1977), or 'errors' in contemporary language, on the manifestation or 'visibility' of core natural processes.

On the pendulum's second appearance, the 'typical pendulum experiment' is criticised because it is 'cleaned up' and used just to teach science content – that the 'period of a pendulum depends on the length of the string and the force of gravity' – and not scientific process skills (NRC 2006, p. 126). In contrast to these 'bad' pendulum practical classes, on the pendulum's third appearance a 'good' class is described over two pages in a highlighted box. In this class, teachers are first advised to demonstrate swinging pendulums, then in a very guided fashion to have students graph the relationships between period and mass, period and amplitude, and period and length, and finally it is suggested that the teacher discuss the importance of obtaining adequate amount of data over a range of the independent variables (NRC 2006, pp. 128–129).

There does not seem to be much especially good or noteworthy about this. Everything about the rich history of the pendulum has been stripped out: no mention of Galileo, Huygens, Newton, Hooke's universal gravitation, timekeeping, clocks, length standards, longitude, shape of the earth, or conservation laws. No connection intimated between science, technology and society; no sense of participation in a scientific tradition. Nothing. Teachers are not even told to talk about these great scientists and their pendulum-based discoveries.

And in this set-piece, nationally distributed, 'model pendulum lesson' teachers and students are told to graph period against length. This is a task with only minimal useful outcomes; such a graph provides a scatter of points that merely establishes a trend. US physics students in the final year of high school, 17–18 years old, could have been so easily asked to additionally plot period against the square root of length. When this is done, nothing is inconclusive: a straight line is obtained from the data, not a scatter of points. Period is seen, as it was by Galileo and Huygens, to not just vary as length, but to vary directly as the square root of length; the conclusion from the data moves from inconclusive $T\alpha L$ to conclusive $T = k\sqrt{L}$. The model lesson tells teachers to 'avoid introducing the formal pendulum equation, because the laboratory activity is not designed to verify this known relationship' (NRC 2006, p. 129). Final-year students in Japan, Korea, Singapore and a good deal of the rest of the world have no such problem, neither should US students.

The graph of period against square root of length shows in a manageable way the dramatic impact of mathematics on physics; without the mathematical notion of square root we see qualitative trends, utilising the square root we see a precise quantitative relationship. Further, this precise relationship will allow the pendulum to be connected with free fall where distance of fall varies as the square of time. All of this is missed in the *Lab Report*, and also missed is the opportunity for richer pendulum-informed teaching of physics. What appears to have happened is what the NRC recognises in another publication:

> As educators, we are underestimating what young children are capable of as students of science – the bar is almost always set too low. (NRC 2007, p. vii)

2.14.5 The Next Generation Science Standards

For the past three years in the US, a new national science education standards document, called the *Next Generation Science Standards* (NRC 2012) has been progressively developed.[26] As the NGSS says:

> The impetus for this project grew from the recognition that, although the existing national documents on science content for grades K-12 (developed in the early to mid-1990s) were an important step in strengthening science education, there is much room for improvement. Not only has science progressed, but the education community has learned important lessons from 10 years of implementing standards-based education, and there is a new and growing body of research on learning and teaching in science that can inform a revision of the standards and revitalize science education. (NRC 2012, p. ix)

The NGSS incorporate and build on the 'existing national documents' but a novel feature is the conscious effort to connect science learning to engineering, to scientific practices, and to make it progressive and cumulative from the beginning of elementary school. These are seen as its *differentia* from 'the existing national documents'. An NGSS press release (10 April 2013) says that instead of students learning by rote, their focus would be on:

> learning how science is done: how ideas are developed and tested, what counts as strong or weak evidence and how insights from many scientific disciplines fit together into a coherent picture of the world.

The pendulum 'ticks all of the NGSS boxes' so as to speak. Very young children, as shown in Japan, Korea and numerous other countries, can profitably and enjoyably engage with pendulum activities (Sumida 2004; Kwon et al. 2006).[27] It is not accidental that Jean Piaget used the pendulum for his investigation of the progressive development of children's scientific reasoning ability, especially their identification and control of variables (Bond 2004). The sophistication of pendulum activities and their relation with other areas and topics in science can be enhanced with progression through school; obvious connections with mathematics, technology and engineering can be made, and even connections with chemistry (De Berg 2006). The full range of process skills (data collection and representation, hypothesis generation), methodological skills (generating hypotheses, evaluating these against evidence, theory testing and so on) and model construction can all be cultivated using pendulum classes (Kwon et al. 2006; Stafford 2004; Zachos 2004).

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[26] The 320pp draft is available free from the National Academies Press website; it is titled *A Framework for K-12 Science Education*. Background studies for the NGSS are in NRC (2007).

[27] An excellent pendulum booklet is produced for Japanese elementary students. Galileo's image occupies the entire front cover while Huygens' image occupies the entire rear cover – a nice comment on the universality of science and its ability to be embraced by cultures beyond its original European home. Japanese students, at least, can gain some sense of participation in the scientific tradition and their indebtedness to those that have gone before.

It remains to be seen how the pendulum will feature, in the final NGSS document but the signs are not good. In the current (2012) draft the pendulum is mentioned four times and each time it is in connection with the transformation of energy from potential to kinetic forms. This is a level of abstraction way beyond what is needed or called for; it is beyond the life experience of the students; and it reifies the role played by the pendulum in the history of physics and in its social utilisation. The draft document mentions Newton's laws, his theory of gravitation, the conservation of momentum, but no mention of the pendulum that could so easily be used to manifest and make experiential each of these learning goals.

2.15 The International Pendulum Project

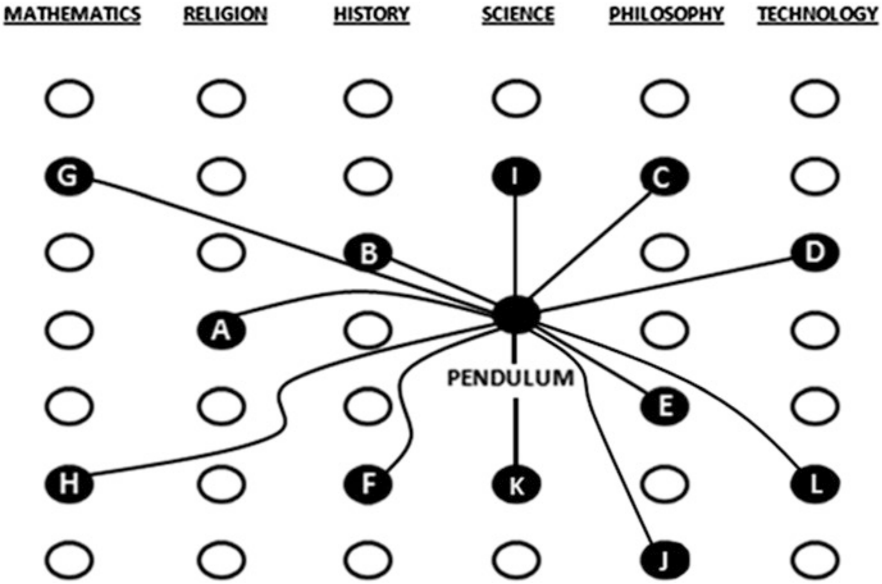
The *International Pendulum Project* (IPP) had its origins with the publication of the book *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion Can Contribute to Science Literacy* (Matthews 2000). The book was about a decade in gestation, has 13 chapters, 1,200 references, and ranges widely over the history, methodology, cultural impact and pedagogy of pendulum studies. Interest in the subject matter of the book was sufficient to bring a large international group of scholars together for conferences at the University of New South Wales in 2002 and again in 2005. Participants recognised the need for teachers and students to be more aware of the important role played by the pendulum in the history of science, and to investigate and promote better and more enriched pendulum teaching in schools.

Scholars from 20 countries contributed to the IPP, and their research appeared in three special issues of the journal *Science & Education* (vol.13 nos. 4–5, 7–8, 2004, vol.15 no.6, 2006). Thirty-three papers from these issues were published in the anthology *The Pendulum: Scientific, Historical, Philosophical and Educational Perspectives* (Matthews et al. 2005). Importantly the contributors came from education, physics, cognitive science, philosophy and history. It is the cross-disciplinary input that gave the IPP its distinctive strength.

2.16 Conclusion

The NGSS gives three reasons for producing updated standards in the USA, one of which is that there is a 'growing body of research on learning and teaching in science' that can be utilised. Due caution should be exercised about such claims. In the 1950s and 1960s, the 'growing body of research on learning and teaching' gave us Behaviourism, which has now disappeared without educational trace; in the 1980s and 1990s, the 'growing body of research on learning and teaching' gave us Constructivism with all its well-known philosophical and pedagogical problems (Matthews 2000a, 2012). Good understanding of teaching and learning is certainly needed, but the improvement of curricula does not flow just from knowledge about *how* to better teach and learn material, but rather it flows from knowledge of *what* material to teach and learn, and *where* to place the topics and concepts in state and national standards. This is where a richer understanding of the history and philosophy of pendulum studies and utilisation (and of course of all other topics) can well contribute to science education. It can make for better curricula and for better connections between disciplinary strands in curricula.

The following diagram, where the columns represent curriculum subjects and the circles topics within subjects, displays the integrative curricular function of history and philosophy.[28]



A. The design argument
B. European voyages of discovery
C. Aristotelian physics and methodology
D. Pendulum clock
E. Idealisation and theory testing
F. Timekeeping and social regulation
G. Geometry of the circle
H. Applied mathematics
I. Measurement and standards
J. Time
K. Energy
L. Geodesy

The content of the school day, or at least year, can be more of a tapestry, rather than a curtain of unconnected curricular beads. The latter is a well-documented problem with US science education, with its fabled 'mile wide and one inch thick' curricula (Kesidou and Roseman 2002). But pendulum motion, if taught from a

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[28] The idea for this visual representation of the argument comes from a AAAS lecture of Gerald Holton, subsequently published as Holton (1995). For elementary schools, READING could be added as a column.

historical and philosophical perspective, allows connections to be made with topics in religion, history, mathematics, philosophy, music and literature, as well as other topics in the science programme. And such teaching promotes greater understanding of science, its methodology, and its contribution to society and culture. But such connections first need to be recognised by curriculum writers and by teachers charged with implementing curricula or achieving standards; this raises the whole question of HPS in pre-service or in-service teacher education, but that is a different subject for a different chapter.

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Chapter 3
Using History to Teach Mechanics

Colin Gauld

3.1 Introduction

The history of mechanics serves a number of functions in science education.[1] The first is its *cultural* function in which appeal to history is used to teach about the changing role science has played in society in the past and the nature of science as it is portrayed in the activities of scientists of old. There is also cultural value in simply knowing about the past and allowing it to inform our attitude to the present progress of science. The second is its *disciplinary* function in which the history of science is used to teach the concepts of science more effectively (Gauld 1977). The similarity between the concepts in the history of mechanics and the ideas which students appear to adopt now has been frequently commented upon, and many have expected history to provide clues about how better to teach those concepts which are difficult for students to learn.

In this chapter a survey of the history of mechanics from the time of Aristotle is presented followed by some of the contributions which this history can make to the teaching of mechanics at various levels of education.

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[1] I thank the anonymous reviewers whose insightful comments led to significant improvements in the content and the structure of this chapter.

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3.2 A Brief History of Mechanics from Aristotle to Newton and Beyond

3.2.1 Aristotle

The history of mechanics right up to the time of Isaac Newton partly involved the untangling of three components of motion in the real world: the nature of the body moved, the cause of the motion and the resistance against which the motion of the body took place. The dominant view over the whole of this period was that of Aristotle who lived from 384 to 322 B.C.

Aristotle distinguished between two types of motion[2] – natural and violent (Aristotle no date a, hereafter referred to as *Physics,* 4.8). The downward motion of heavy bodies or the upward motion of light bodies is natural as they move towards their natural place at the centre of the universe (the centre of the earth) or the upper spheres respectively. Any departure from natural motion was called "violent" or "compulsory" motion and was the result of a cause outside of the body (*Physics,* 8.4). This meant that a body could move off in other directions than up or down at a speed other than that which was "natural" if an external mover impelled it.

Rest occurred when a body reached its natural place or when its tendency to do so was impeded by a cause which prevented this natural motion. The first Aristotle called "natural rest" and the second "unnatural rest" (*Physics,* 5.6).

In Aristotle's world all motion took place against resistance of different sizes (*Physics,* 4.8) since motion occurred as bodies moved through corporeal substances of different density (or viscosity) or over surfaces of varying degrees of roughness.

A fundamental axiom in Aristotle's views about motion was that all that moves is moved by something else (*Physics,* 7.1). This meant that even the natural motion of bodies was caused by something else and, as far as it is clear in his writing, he saw the tendency for heavy bodies to move downwards as the essential meaning of the term "heavy" (*Physics,* 8.4). Weight was not a property of the body as such but only an expression of this tendency (Aristotle no date b, hereafter referred to as *Heavens*, 3.2). For a heavy body at rest, one of the causes of its later downward movement was the *removal* of the external impediment preventing its natural motion (*Physics,* 8.4). For violent motion the cause was always outside of the body and it was necessary that there be contact between the mover and the body moved.

Aristotle's notion of universal resistance to motion was closely related to his belief in the non-existence of the void (Gregory 1999). One of Aristotle's objections was that since the void was nothing, it possessed no properties – not even properties with zero value (*Physics,* 4.8); a body entering one "side" of a "void" would instantly appear at the opposite "side" and so the body would be in two places at the same time.

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[2] For Aristotle "motion" was a term that covered all types of change and what we call "motion" was a change of place – movement from one position to another – called by him "local motion" or "locomotion".

3.2.2 Projectile Motion

The motion of projectiles posed a particular problem for Aristotle. It was easy to identify the cause of its beginning to move since the mover was in contact with the projectile. However, it was not so easy to understand why it continued to move once it had lost contact with the mover. One proposal posited by Aristotle was that the original force moved the projectile which then moved the air which then moved the projectile (*Physics,* 4.8; 8.10; *Heavens*, 3.2). This occurred in successive stages with different portions of air first being pushed and then themselves pushing. Over time the force from the successive portions decreased (*Physics,* 8.10). Another of Aristotle's objections to motion through the void was based on the view that since a medium was necessary for the motion of projectiles and the void contained no such medium, then motion in the void was impossible (*Physics*, 4.8).

Philoponus in the sixth century A.D. saw no sense at all in Aristotle's explanation for the motion of a projectile after contact with the projector was broken.[3] For example, he could see no reason why, when air was pushed forward by the projectile, it then reversed its direction and moved back towards the end of the projectile and then again reversed its direction to push forward on the back of the projectile. He also argued that as the projectile moved forward, air from behind the projectile would immediately fill the space previously occupied by the projectile, so that the air pushed from the front of the projectile would have no space to occupy. Philoponus had a great deal of difficulty believing that its continued motion could be due to this activity of air since one could not initiate the motion of a projectile simply by setting in motion the air behind it.

The solution Philoponus offered was that a motive force was imparted to the projectile by the projector, and he claimed that a projectile would move more quickly in the void than through some medium. Over time the strength of the motive force imparted by the projector decreased and eventually became zero (Franco 2004; Moody 1951b, p. 390).

In dealing with the motion of projectiles, Buridan in the fourteenth century argued against a number of alternative explanations for the continuation of the motion after the projectile had left the projector's hand (Buridan in Clagett 1959, pp. 532–40). He was not happy about Aristotle's notion of the role of the air since a mill wheel continued spinning after the turning force was removed. He reported that when a boat which was being hauled along by ropes was released. It also continued moving although those on the boat felt no wind pushing the sails. Buridan adopted a solution in which a non-decaying impetus was transferred from the projector to the moving body.

Early in his career Galileo (1564–1642) believed that when a projectile left the hand which moved it, it received an impressed force which began to decay (like the heat in a body or the ringing of a bell) as the projectile moved (Galileo 1590/1960, hereafter referred to as *Motion,* pp. 76–80). Thus, a projectile thrown upwards would gradually decrease in speed until the remaining size of the impressed force

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[3] See Cohen and Drabkin (1958, pp. 221–3) and Wolff (1987).

became equal to the weight of the body, and then it would move downwards with increasing speed as the difference between the weight and the impressed force increased. Eventually, when the size of the impressed force was zero, the body would travel at its natural speed until it reached its final destination (*Motion*, pp. 76–89). Something of this notion occurred when a body was allowed to fall from rest since the force which initially restrained the body transferred an impressed force to the body which again allowed the body to accelerate before reaching its natural speed (*Motion,* pp. 90–2).

By the time Galileo had published in 1638 his last work, *Discourses on the Two New Sciences* (Galileo 1638/1974, hereafter referred to as *Discourses*), he had turned from investigating the causes of motion to describing it (although there is some evidence that he now accepted the existence of a non-decaying impetus). On day 4 of his *Discourses,* he presented his theory of projectile motion developed on the basis of the assumption that such motion consisted of two independent perpendicular motions – a uniform horizontal speed and a uniform vertical acceleration. Galileo carried out experiments to determine the trajectory of a projectile which was projected horizontally from a curved section at the bottom of an inclined plane.

3.2.3 Free Fall

One relationship found in Aristotle's writing is that the speed of a moving body is proportional to the impelling force and inversely proportional to the total resistance to its motion (*Physics,* 4.8; 7.2; *Heavens*, 1.6).[4] When falling, the weight functions as the force responsible for the motion. When he referred to speed during a fall, he usually meant something like our concept of average speed. He apparently believed that as a body fell downwards because of the tendency to move towards its natural place, this tendency increased as it neared the centre of the earth and so its weight and its speed increased (*Physics,* 1.8). In other words he was well aware that falling bodies accelerated.[5]

Philoponus accepted the possible existence of the void, and he justified this notion through use of a different relationship between motive force and consequent speed to that used by Aristotle. He argued that a body would move through the void with its maximum speed proportional to its weight. If the void were then to be filled with a medium, this would resist the motion and so decrease the speed by an amount proportional to the density of the medium. Thus his relationship can be expressed in our terms as $S \alpha W - R$.[6]

In the early twelfth century, the position of the Arabic philosopher Avempace was very much that of Philoponus. Avempace believed that bodies were moved by

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[4] If the void were thought of as space with zero density, Aristotle's relationship would imply that bodies would move through it with infinite speed which Aristotle considered to be impossible.

[5] See Aristotle, *Physics*, 5.6; 6.7; 8.9 and *Heavens*, 1.8; 2.6.

[6] See Cohen and Drabkin (1958, pp. 217–21), Moody (1951b, p. 360), and Wolff (1987).

their own nature and that weight was an intrinsic property of a heavy body. Bodies moved through the void with natural speeds that were proportional to their densities and, for him, the only resistance in this case was the distance to be traversed by the body through the void. Motive force was measured by the time taken to traverse a given distance. A medium acted to reduce this natural speed and was therefore an accidental aspect of motion rather than an essential one as Aristotle believed. Avempace had some difficulty accounting for the acceleration exhibited by falling bodies (Moody 1951a, b; Grant 1964, 1965).

In the later twelfth century, Averroes' position was a refinement of Aristotle's. He rejected the notion that bodies moved by their own nature. Motion for him was the overcoming of resistance and motive force was measured by the product SR. He rejected the possibility of motion in the void on the grounds that, because S was proportional to F/R, the speed in the void would be infinite.

The Aristotelian Bradwardine (1290–1349) accepted the arguments that were levelled by Avempace and others against Aristotle's notion that the speed of a body through a resisting medium was proportional to the ratio of the motive force to the resistance. For example, Archimedes had shown that for a body falling through a medium, if the downward motive force was equal to the upthrust (i.e. the resistance to downward motion), the body should neither float nor sink (Moody 1951b, p. 399). On the other hand, Bradwardine was also not happy with the proposal that the speed was determined by the difference between the motive force and the resistance which provided some support for the possibility of a void against Aristotle's strong objections. He argued that when Aristotle referred to proportionality, he did not mean simple proportionality but geometric proportionality.[7]

Buridan considered gravity to be a force which added impetus to the falling body. This impetus was an internal motive force which was directly proportional to the speed. Gravity added impetus so that the speed increased; this, in turn increased the motive force which impelled the falling body so increasing the impetus and thus the body accelerated (Drake 1975c).

One of the problems discussed by medieval thinkers was how to describe the motion of bodies as clearly as possible. While much energy was expended on trying to explain the causes of motion, it became clear, in the fourteenth century, that this question could be placed to one side and that one could concentrate on the kinematical rather than on the dynamical aspect of motion. An obstacle to this was the lack of a precise way of characterising speed. Aristotle (and many of his commentators) only referred to the time taken to travel a certain distance (so that a faster object covered the distance in a shorter time) or the distance travelled in a certain time (so that a faster object covered a greater distance in the time). In our terminology they were using the notion of average speed. In the fourteenth century the notion of instantaneous speed was introduced for a body of which the speed was changing.

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[7] See Dijksterhuis (1961, pp. 190–1). This relationship means, in our terms, the following: when the speed, S, doubles, the ratio, motive force (F)/resistance (R), is squared or, more generally, when $K = S_1/S_2$, $\frac{F_2}{R_2} = \left(\frac{F_1}{R_1}\right)^k$. In modern terms this means $S \propto \log\left(\frac{F}{R}\right)$.

This was first understood as the distance travelled if the body continued, from that time, for a given duration, with that (now constant) speed.

With this concept of instantaneous speed came the notion of uniformly accelerated motion in which the speed increased in equal increments in equal intervals of time, and, in Merton College, Oxford, during the first half of the fourteenth century, the mean value theorem was discovered. This stated that if a body moved so that its speed changed uniformly from zero to S in a time, T, then the distance travelled would be the same as for a body which travelled for a time, T, at half that speed ($S/2$).

Nicole Oresme introduced a method of presenting information about qualities (such as hotness and whiteness) using two perpendicular axes with information about extension in space or time along the horizontal axis and vertical lines distributed along this axis to represent the intensity of the quality (such as speed) of interest (Durand 1941). Uniform speed was thus represented by a rectangle where the constant height represented a constant speed during the time, T, while uniformly accelerated motion was represented by a right-angled triangle. It became clear that in this representation, the area of the figure so produced (at least in these two cases) was equal to the distance travelled by the body. However, at this stage, there was no indication that such a motion might be related to what occurred in free fall.

In thinking about the variation in the speed of a falling object, Isaac Beeckman (1588–1637), 200 years after Oresme and a younger contemporary of Galileo, took the work of Oresme as his starting point and envisaged that the line which represented time was divided into n segments. He imagined that instead of the speed increasing steadily throughout the time interval, it proceeded in a series of "jerks" (Dijksterhuis 1961; Beeckman in Clagett 1959, pp. 417–8).

Beeckman illustrated his theory with the diagram shown in Fig. 3.1 in which AE represents time and the horizontal lines represent speed.

The distance travelled by the body is proportional to the sum of the areas of the four rectangles in the diagram. If the number of intervals into which AE has been divided is increased, the total area of the small triangles equivalent to a, b, c and d decreases so that in the limit the distance travelled by the body during the time A to E is proportional to the area of the triangle AEF. Thus Beeckman was able to reason in this way without having to introduce a definition of instantaneous speed as the ratio between two vanishing quantities.

Early in his life Galileo was very much influenced by the works of "superhuman Archimedes" (*Motion*, p. 67), and he developed the notion that for falling bodies, it was not the weight that was the determining factor but the density so that the speed in this case was proportional to the difference between the density of the body and the density of the medium. As a result he argued against Aristotle's concept of absolutely heavy bodies (i.e. bodies which always, regardless of the circumstances, fell towards the centre of the universe) and absolutely light bodies (i.e. bodies which always moved away from that centre). Instead, if the density of a body was less than that of the medium (e.g. wood in water), the body would move upwards, while if its density was more than that of the medium (e.g. wood in air), the body would move downwards (*Motion,* pp. 23–6). He claimed that bodies in a medium did not weigh their natural weight but only the difference between that weight and the

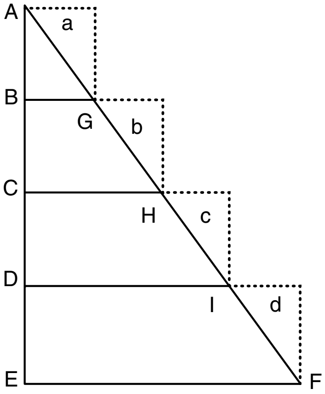

Fig. 3.1 Beeckman's treatment of uniformly accelerated motion. Line *AE* represents the time which has been divided into four equal intervals *AB*, *BC*, *CD* and *DE*. The speed between *A* and *B* is represented by a line of constant length equal to *BG*; between time *B* and *C,* the speed is represented by a line of constant length equal to *CH*; between *C* and *D,* the speed is represented by lines equal in length to *DI*; and between *D* and *E,* the speed is represented by lines equal in length to *EF*

weight of a volume of the medium equal to that of the body. In a vacuum the weight of a body would be its natural weight (*Motion,* p. 46). One of Galileo's conclusions at this stage in his life was that bodies with the same density would move downwards with the same speed in a vacuum, while bodies with different densities would move with speeds proportional to their densities.

At one time Galileo believed that the motion of a falling body was a uniform increase in speed with equal intervals of distance, but in his *Discourses* (pp. 159–60), published towards the end of his life, he argued against this notion and opted for a uniform increase in speed with equal intervals of time. This concept was verified through his experiments with balls rolling down inclined planes (Hahn 2002). By this time Galileo was convinced that all bodies fell in a vacuum with the same acceleration.[8]

3.2.4 Forced Motion

Aristotle developed a relationship between the external force, the weight, the distance traversed over a surface and the time taken to move this distance. For Aristotle (*Physics,* 7.5) but in our modern terms

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[8] In days 3 and 4 of his *Discourses* (pp. 158–9), Galileo indicated a lack of interest in extrinsic, efficient causes such as forces (Machamer 1978) and sought firstly to describe the motion of a falling body. For Descartes and Newton the search for such causes was much more central to their investigations.

$$\frac{D}{T} \propto \frac{F}{W} \text{ (as long as } F > R\text{)}$$

In this relationship, W is a measure of the resistance to the motion which is directly related to the weight. This relates to the difference in the motions of heavier bodies (such as ships) and lighter bodies (such as boxes), the former requiring many people to pull with a certain speed while the latter requires fewer people to pull with the same speed across sand. Aristotle was also aware of the fact that a certain force was required to commence the motion and that, below this force, the body would remain at rest. Bradwardine's modification, mentioned previously, was also applied in the Middle Ages to the situation of forced or violent motion.

3.2.5 Circular Motion

Aristotle believed that circular motion was the only motion which could be eternal since there is no starting or finishing point with a circle. Motion along a straight line must cease when the end is reached because, for Aristotle, an infinite straight line was an impossibility (*Physics,* 8.8; 8.9). Circular motion was perfect and eternal and was therefore appropriate for the planets and the planetary spheres, the motive force for which was "the unmoved mover" (Koestler 1968, p. 61; Aristotle, *Heavens*, 3.2). A body undergoing circular motion, in one sense at least, did not change its place.

The difference between motion on the earth and in the heavens which Aristotle emphasised was downplayed by Buridan who believed that the planets and stars could also be impelled by his impetus rather than by the "intelligences" which Aristotle presumed.

Galileo argued that if a ball ran down one inclined plane and then up another, it would reach the same height from which it began. If the second inclined plane was lowered, the ball would have to travel further before this height was reached. In the limit, Galileo reasoned, the ball would continue forever along a horizontal plane at the speed it had reached after its initial fall (Galileo 1632/1967, hereafter referred to as *Dialogue*, pp. 145–8). However, for Galileo, this "plane" was not flat but followed a circle around the earth. In this way he reached his concept of circular inertial motion.

René Descartes (1596–1650) realised that in the light of his second natural law, which referred to a body's tendency to move in a straight line, motion in a circle would involve a tendency (*conatus*) for the body to pull away from the centre (Descartes 1966, pp. 217–8).

The conical pendulum played a central role in the thought of both Descartes and Christiaan Huygens (1629–1695) as they considered the nature of circular motion. Since a force is necessary to draw a pendulum aside from the vertical (see Fig. 3.2b), there must be a similar force in the case of a conical pendulum rotating in a circle with the string at an angle to the vertical (see Fig. 3.2c). This Huygens called a centrifugal force. Huygens viewed uniform circular motion (along with uniform

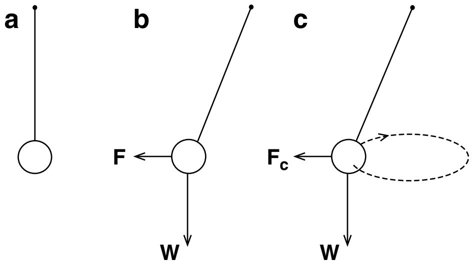

Fig. 3.2 The role of centrifugal force in the conical pendulum

rectilinear motion) as a type of inertial motion. He developed Descartes' view and showed mathematically that the tendency to flee from the centre was given by mv^2/r (Dijksterhuis 1961, pp. 368–70).

3.2.6 *Impact*

Towards the end of his life, Galileo showed interest in the fact that a moving hammer could drive a nail into wood further than if the hammer simply rested on the nail, and he sought to find the relationship between the effect of the moving hammer and its mass and speed (*Discourses,* pp. 285–8).[9]

Descartes proposed seven laws of impact by which to predict the outcome of a collision between two bodies when the initial conditions were known. Because of some of the premises of Descartes' philosophical system (Descartes 1966, pp. 216–8; Blackwell 1966; Hall 1960–1962), a number of these laws gave faulty outcomes. For example, Descartes believed that no matter how fast it was travelling, a smaller body could not cause a larger stationary body to move.

Huygens was very critical of Descartes' laws of impact and used a methodological device to show that they were inconsistent among themselves. In the case of a smaller body striking a stationary larger body, Huygens imagined an observer on a boat moving alongside the smaller body so that it appeared to be at rest (Dijksterhuis 1961, pp. 373–6). From the observer's point of view, the collision was now transformed into one in which a larger body collided with a stationary smaller body in which Descartes claimed motion was transferred. Huygens worked within a purely kinematic framework and he had no use for the concept of force. He assumed that, in a collision, if the speed of one body was reversed unchanged in magnitude, then the speed of the other body would also be reversed with no change in magnitude (Erlichson 1997b).

Gottfried Leibniz (1646–1716) was another follower of Descartes who was critical of Descartes' laws of impact. He used his principle of continuity (Leibniz 1692/1969, pp. 397–404) to show that Descartes' laws were inconsistent among themselves. This principle says that if two trends are associated then, if the changes in one are continuous, the changes in the other are also continuous. For example, in collisions

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[9] A younger contemporary of Galileo, Marcus Marci, also developed a theory of impact (Aiton 1970).

the outcome speed should be associated with the incoming speed in this way. Leibniz argued that, for the collision between a smaller body with a stationary larger body, if one gradually increased the weight of the smaller body, a point would be reached when the weights of the two bodies were equal in which case Descartes claimed that the moving body would stop and the stationary body would move off with the same speed as the originally moving body. This would mean that a gradual increase in weight of the first body would mean a sudden change, for the second body, from no speed to a speed equal to that of the first. This behaviour was contradicted by Leibniz's principle of continuity.

Leibniz went on to develop his own laws of impact based on three axioms (Garber 1995):

1. The relative velocity of the two bodies is the same before and after the collision.
2. The sum of vector $m\mathbf{v}$ is conserved in the collision.
3. The sum of mv^2 is conserved in the collision.

Unlike Huygens, Leibniz approached impact from a dynamical point of view and held a positive concept of force (*vis*) which he argued was found in two forms – dead and living. Dead force (*vis mortua*) was that which acted when bodies were at rest in equilibrium; living force (*vis viva*) was the force in moving bodies and which was transferred during collisions. Leibniz claimed that *vis viva* was measured by mv^2 rather than by scalar $|mv|$ as Descartes had believed.

3.2.7 Pendulum Motion

Another type of motion of interest to Galileo was that of the pendulum (*Motion,* p. 108). Early on, by watching the swing of a censer in the cathedral at Pisa, he concluded that the time of oscillation was constant regardless of the amplitude and was also independent of the weight of the suspended body (*Dialogue*, p. 450; Matthews 2000, pp. 95–107). The difference the weight made was that the pendulum would swing for a much longer time if the suspended body was heavy.

Galileo's conclusion that the period of a pendulum was independent of its amplitude was probably an inference from his observations of pendulum motion with small amplitude, and his theoretical demonstration that the time for a body to move down a chord to the lowest point on a circle was the same regardless of the starting point.[10]

Huygens showed that a pendulum moving along a cycloidal path would be isochronous regardless of the amplitude of the motion.[11]

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[10] See Ariotti (1968), Erlichson (1994, 2001), Gauld (1999), MacLachlan (1976), and Naylor (2003).

[11] Further details about the pendulum in history and teaching can be found in Matthews et al. (2005).

3.2.8 Isaac Newton

In Newton's day laws of motion were designed to help explain the collision process between two bodies,[12] and this enables us to understand the meaning of his three laws (which function as axioms in his system). In his *Principia* (1729/1960) *Law 1* tells us the state of a body when no interaction occurs, that is, Newton described the natural state of the body, so that, when a force was exerted, its action could be recognised. *Law 2* tells us that, when a collision takes place, the change in the product, $m\mathbf{v}$, for one body is proportional to the force of impact, while *Law 3* indicates that the forces which the two bodies exert on each other during the collision are equal and opposite. It is interesting to note that there is no mention of time in Newton's statement of his second law. However, in other parts of the *Principia*, Newton makes clear that the change in vector $m\mathbf{v}$ is also proportional to the duration of the action of the force.[13] For example, in his discussion of the motion of a body which experiences a resistance proportional to the square of the speed (*Principia*, Book 2, Proposition 9), the accelerating force is proportional to the change in velocity divided by the time interval.[14]

Early in his career Newton (1642–1727) used a body bouncing along a polygonal path inside a circular container beginning with four segments and increasing the number until the body moved along a circular path to show that the centrifugal force was the same size as Huygens had found, namely, mv^2/r.[15] In the *Principia* Newton tackled the problem of motion under the action of a central force. This led him to the conclusion (*Principia*, Book 1, Proposition 4, Corollary 1) that it was not a centrifugal force that acted on a body moving in a circle to pull it from the centre but a centripetal force which continually caused a departure from the straight line path defining the body's inertial motion (see *Principia*, Book 1, Proposition 1; Erlichson 1991).

Projectile motion is treated in the *Principia* not only when the projectile meets no resistance from the medium through which it is travelling but also (in Book 2) when it moves through a resisting medium. To test his assumptions about the effect of resisting mediums, Newton used pendulums and falling bodies moving through water and air.[16]

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[12] See Arons and Bork (1964), Dijksterhuis (1961, pp. 464–77), and Erlichson (1995).

[13] Time does not appear in Newton's second law because in a collision the duration of the forces on the two bodies involved is the same.

[14] See Gauld (2010, equation (3)), Pourciau (2011), and Westfall (1971, pp. 481–91). In Book 1 of the *Principia,* Newton developed the implications of his three laws for the action of central forces on bodies which experience no resistance (other than that of the "force of inertia"). It is in this book that he derived Kepler's laws of planetary motion from an inverse square of force. In Book 3 Newton applied the insights of Book 1 to observation made on the motion of planets, the moon and comets. In Book 2 his Laws are applied to a variety of other situations including the motion of bodies through resisting mediums, fluid flow and waves. Densmore (1995) is an excellent guide to the *Principia*. Pourciau (2011) presents a different view of the nature of Newton's second law than that presented here.

[15] See Herival (1965), Newton and Henry (2000), Stinner (2001), and Westfall (1971, pp. 353–55).

[16] See *Principia*, Book 2, Sect. 6, Gauld (2009, 2010).

Pendulum motion was dealt with by Newton in Book 1 of the *Principia* (Propositions 50 and 52) in which he showed much more elegantly than Huygens did that a pendulum moving along a cycloidal path took the same time for each oscillation regardless of the amplitude. He also implied that, for small oscillations, the periodic times of a cycloidal and a circular pendulum of the same length were equal (Gauld 2004).

Thus Newton's system successfully dealt with all of those problems which occupied his predecessors and provided one theory by which free fall, forced motion, motion down an incline, impact, projectile motion, circular motion and the motion of the pendulum could be understood.

3.2.9 Beyond Newton

After the publication of the *Principia*, a debate arose between those who followed Newton and those who followed Leibniz as to what was the appropriate measure of the force of a moving body, $|mv|$, $\boldsymbol{mv}$ or mv^2. The Leibnizians referred to experiments in which a falling or colliding ball left an impression in soft clay to support their case that it was mv^2. People, such as Jean d'Alembert, John Desaguliers and Thomas Reid claimed that the dispute was simply a terminological one and depended on what aspect of motion was the focus of interest – time or distance (Boudri 2002, p. 110).

However, for Leibniz himself the issue of importance was his own view of the nature of matter and force (Gale 1973). He, like Descartes, believed that the amount of force in the world was constant but, unlike Descartes, he believed that inelastic collisions showed that the scalar $|mv|$ of Descartes was not conserved. On the other hand he argued that the vector $\boldsymbol{mv}$ of Newton could either be positive or negative rather than always positive as was the case with Leibniz's mv^2. Of course, mv^2 was not conserved in inelastic collisions, but Leibniz claimed that it was conserved in the elastic particles which he believed made up the colliding bodies (Gauld 1998a).

The dispute lingered on until the late 1800s and eventually petered out without any definite contribution resolving the issue.[17] Boudri (2002) claimed that the change which contributed most to its resolution was from a dependence on a metaphysics of substance to that of a metaphysics of relations. The various aspects of the past concept of force – $|mv|$, $\boldsymbol{mv}$ and mv^2 – were seen to be constructs of the quantities involved in the study of motion (such as distance and time) and the notion of force as a cause became less dominant (see also Coelho 2010). In addition, the move from sole consideration of forces of impact in which the "force of motion" was of prime importance to an acceptance of force-at-a-distance as an external impressed force which was central to Newton's system (though not so much for his followers) meant that arguments about the force of motion became of decreasing significance (Papineau 1977). Lagrange's formulation of the laws of mechanics was

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[17] See Hankins (1965), Iltis (1970, 1971, 1973), Laudan (1968), and Papineau (1977).

in terms of kinetic energy (T) and potential energy (V) which depend only on mass, position and time. The concept of force does not explicitly appear but is implicitly present as $\partial V/\partial x$ (e.g. see Hanc et al. 2003). Ernst Mach attempted to eliminate the notion of force altogether from Newton's system of mechanics.[18]

3.3 History of Mechanics and the Nature of Science

3.3.1 Some Issues in the History of Mechanics

Throughout the history of mechanics, the concepts of distance and time have been basic and generally presumed to be directly apprehended in experience. On the other hand those of force and mass have not and could only be experienced through their effects. Both concepts have undergone significant change in the minds of early scientists and in their role in mechanics. For some, the notion of force as a cause is itself a source of concern as it was seen as an unnecessary metaphysical intrusion into a science which should be free of metaphysics.

A major contribution to the development of mechanics was the use of mathematics to represent motion, and changes to this mathematical representation helped to promote mechanical research. The logical framework of Euclid's geometry was a significant factor in determining the way in which mechanical ideas were to be presented. Both Galileo and Newton used the definition, axiom, proposition, theorem and problem structure in their major works. These issues will be dealt with in more detail in what follows.[19]

3.3.1.1 Force

One of the major difficulties in the development of mechanics was the lack of a clear definition of force. The notion arose from the ideas of cause and effect with force as the cause and motion as the effect. However, it became clear that the concept of force was difficult to usefully define apart from its effects and, for some people, force itself became an effect of motion since motion was used to define it. Some adopted the view that, since force was such a difficult concept to define, they would limit their study to that of motion itself and so, for example, Galileo referred rarely in his *Discourses* to the concept of force. On the other hand both Leibniz and Newton adopted a view that force was a real (although difficult to define) entity which was to be measured by the effects which it produced.

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[18] See Mach (1893/1960, pp. 303–07; 319–24), but see also Bunge (1966).

[19] Coelho (2012) provides a detailed analysis of conceptual issues in mechanics.

The history of mechanics to the time of Newton (and beyond) has largely been concerned with drawing distinctions between concepts related to the notion of force. Some of these are:

- Force as a cause of velocity or as a cause of acceleration
- External force and internal force
- Force as a cause of acceleration and inertia as a resistance to acceleration
- Inertia as a force of persistence (momentum) or as a force of resistance (mass)
- Inertia as a force within matter or as a property of matter
- Contact force and force-at-a-distance
- The effect of a force over time (momentum) and the effect of a force over distance (kinetic energy)

Early in the development of mechanics, the concept of force covered a number of ideas that we now distinguish. For example, it included concepts of power, work, kinetic energy, momentum and action. One difficulty in the history of mechanics was that of seeing the importance of these distinctions and encouraging the community of scholars to accept the need for establishing and maintaining them. For example, Huygens worked with the expression mv^2 without seeing its importance, while Leibniz took it as the fundamental measure of the force of motion. On the other hand, Newton made no use of mv^2 but related force to the change in mv.

This issue came to a head when the dispute over the true nature of force – Newton's mv or Leibniz's mv^2 – was in full swing. Newton's followers referred to the collisions between bodies in which mv was conserved, while Leibniz's followers referred to experiments in which springs were compressed or soft clay was depressed by the action of moving bodies in which equal deformations occurred for bodies with equal mv^2.

For a long time the free fall of a body was attributed (e.g. by Aristotle) to its tendency to move to its natural place and was not considered to be, like violent motion, the result of an external force. Neither Galileo nor Descartes saw free fall as the paradigmatic example of forced motion but simply as an example of uniformly accelerated motion.

A barrier to the progress of mechanics was the implicit assumption that there were two types of natural motion – rectilinear and circular. Galileo believed that inertial motion when no force acted was in a circle about the centre of the earth. Descartes, while believing that circular motion was unnatural and involved the action of a centrifugal force, still saw it as a state of equilibrium (Westfall 1971, pp. 81–2). Huygens saw a close analogy between uniform rectilinear motion and uniform circular motion (Westfall 1971, pp. 170–1). Newton on the other hand was clear about the proposition that inertial motion was rectilinear while circular motion required a centripetal force. In the eighteenth century d'Alembert treated circular motion as inertial and reintroduced the concept of centrifugal force which was required so that the resultant force on a body undergoing uniform circular motion was zero.[20] The generalised mechanics of Lagrange and modern rotational

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[20] d'Alembert's approach to the solution of problems of motion is still alive today in some engineering contexts (see Newburgh et al. 2004). See also the discussion of inertial forces by Coelho (2012), and Galili (2012).

mechanics also treats the circular motion of solid bodies about a fixed axis as inertial and replaces the concepts of force, velocity and acceleration with those of torque, angular velocity and angular acceleration.

3.3.1.2 Inertial Mass

Another serious obstacle to progress in the development of mechanics was, initially, lack of an adequate concept of (inertial) mass and the lack of a distinction between mass and weight (Franklin 1976). Weight is an easily experienced characteristic of bodies but was attributed to different things by different people. For Aristotle and most of those influenced by him right up to the seventeenth century, weight was simply an expression of the tendency of bodies away from their natural place to move towards that place. This was associated with volume which was the property of the body most directly related to weight. There was an awareness that, for bodies made of different material, different weights could be associated with the same volume thus giving rise to the notion of density (see Biener and Smeenk 2004). Certainly the difference between the densities of water and air was known to Aristotle (*Physics,* 4.8). Without a notion of mass, the resistance of bodies to change of motion (and especially to change from rest to motion) was attributed to other factors than inertial mass.

Huygens possessed an embryonic concept of the resistance which mass presented to attempt to change the motion of a body while Newton, in the *Principia* at least, was clear about this idea. He defined in his list of definitions what he called the *vis insita* or the *vis inertiae* (*Principia*, Definition 3) by which a body maintained its state of rest or uniform velocity in a straight line and resisted the actions of external forces.[21] Not until the time of Newton did mass take on the character of inertia which we attribute to it today.

3.3.1.3 Mathematics

In the Middle Ages the concept of speed was distinguished from that of distance or time which could be measured. Speed was a quality more like charity or wisdom which could be more or less intense but which could not be measured.

The development of an adequate framework for the study of kinematics was hindered by the lack of a clear definition of instantaneous speed. Up to the fourteenth century speed was defined in terms of the distance travelled in a certain time or the time taken to travel a certain distance. If one of these variables was not the same for the bodies, it was not generally possible to compare speeds. The most this notion could lead to was a qualitative version of our concept of average speed.

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[21] Gabbey (1980) argues that, in Newton's *Principia*, there are two concepts of *vis inertiae* that associated with the persistence of motion and measured by $m\boldsymbol{v}$ and that associated with the change of velocity and measured by $m\boldsymbol{\Delta v}$.

Another problem was that a dependence on the Euclidean theory of proportions restricted ratios to those between-like quantities, and so the notion of speed as a ratio between distance and time was prohibited. In the fourteenth century interest was turned to uniformly accelerated motion in which the velocity changed from moment to moment. The closest to a definition of instantaneous speed at that time was the constant speed which an accelerating body had at a particular point in time if it were to cease accelerating and continue with that speed. This was the definition which Galileo used in his experiments on the parabolic trajectory of horizontally projected falling bodies. The development of the calculus by Leibniz and Newton was the necessary tool for defining instantaneous speed in a more useful way.

A broader issue was the role of mathematics in understanding the nature of mechanics. Galileo was the first to develop a comprehensive system of mechanics which was thoroughly mathematical in nature and which was presented as a series of logical deductions resting on axioms which were not always self-evident.[22] In both Galileo's *Discourses* and Newton's *Principia*, geometrical representations dominate and the structure of each parallels that of Euclid's mathematics.

3.3.2 Some Philosophical Issues

There are many philosophical issues arising out of the history of mechanics. Some of these relate to the nature of the concepts employed in the subject, while others are related to deeper concerns with the nature of the reality (if any) underlying the phenomena under investigation. There are also questions relating to the way scientific activity is carried out and scientific knowledge validated. Some of these issues are discussed below.

3.3.2.1 Meaning Matters

Even within the history of mechanics, a similar form of words may represent quite different meanings because of the particular philosophical or cultural framework in which the statement is embedded. Descartes (1966, pp. 216–7) and Newton (1729/1960) presented laws which state that, in the absence of external forces, a body will move with constant speed along a straight line. Gabbey (1980) pointed out that although the law as a description of what happens might be the same for these two writers, its meaning for them was significantly different. For Descartes the law provided the explanatory basis for understanding, for example, what

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[22] Following his definition of naturally accelerated motion, Galileo's postulate in his *Discourses* related to motion down inclined planes: *I assume that the degrees of speed acquired by the same moveable over different inclinations of planes are equal whenever the heights of those planes are equal* (*Discourses*, p. 162). This postulate would not have been self-evident to Galileo's contemporaries and later in the *Discourses* he deduced it as a theorem!

happens in collisions between bodies. He believed that rest was a different state from motion and that a force was necessary to maintain rest as well as to maintain motion. Descartes denied the existence of inertia and claimed that the apparent inertial properties of bodies were simply due to the redistribution of "motion" among colliding bodies. The force exerted by a moving body was *size x speed.* For Newton, rather than being explanatory, the law simply provided a norm, departure from which indicated the existence of a mechanical process which was then explained in terms of his second and third laws. He believed that rest and uniform rectilinear motion were equivalent states. The force exerted on a moving body was equal to *mass x change of velocity*. The meaning of the laws depends on the whole framework within which each worked.

It is also important to note that the *Physics* of Aristotle also contains a similar statement of Newton's first law: "a thing will either be at rest [in a void] or must be moved ad infinitum, unless something more powerful gets in the way" (4.8). He based this conclusion on an argument that, in the void, one point is no different from any other point so there was no reason for the body to stop here rather than there. However, in Aristotle's scheme of things, his conclusion only provided a reason for rejecting the existence of the void because he believed that the statement above was absurd since bodies always stopped.[23]

3.3.2.2 Idealisation in Mechanics

Science is essentially an attempt to understand the natural world, and progress is generally made when what is experienced is explained by what is not experienced. The matter in Aristotle's world was understood in terms of the four basic (but unseen) ideal elements: earth, fire, water and air. In later science mechanical phenomena were understood as consisting of ideal, law-like behaviour along with impediments or intrusions which caused departures from this law-like behaviour (see Matthews 2004). For example, while a vacuum did not actually exist in the experience of the Greek thinkers (although it could be conceptualised), Philoponus believed that if bodies moved through a vacuum their speeds would be proportional to their weights. The mediums through which they travelled imposed a resistance which caused departure from this behaviour. Galileo's experiments were designed to show this law-like behaviour in spite of the existence of impediments which caused the results to be other than ideal.

What is considered to be the ideal behaviour, of course, depends on one's view of the world and can sometimes be shown to be mistaken. Philoponus' view was eventually replaced by that of the mature Galileo who argued that, in a vacuum, all bodies would fall with the same speed. Newton claimed that an isolated body, free from the influence of all other bodies, would travel in a straight line at a constant

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[23] Galileo's notion of inertial motion was expressed in similar terms (see *Discourses*, p. 197), but for him the path was not a straight line but a circle around the earth (*Dialogue,* pp. 147–8). On the status of Newton's first law among physicists over the last two centuries, see Whitrow (1950).

velocity, while Mach suggested that if the inertial properties of the body were determined by the overall matter in the universe, removing the influence of this matter would also destroy the inertial properties of the remaining body.[24,25]

3.3.2.3 Empiricism Versus Realism in Mechanics

Throughout the history of science, there have been two main trends in the way in which the purpose of scientific activity has been conceived, namely, empiricism, that is, understanding the phenomena perceived by our senses (and nothing more), or realism, that is, understanding the nature of the reality which lies behind what we perceive. For empiricists, many of the constructs of physics (including the idealisation mentioned above) which cannot be directly experienced are simply devices for relating in an economical way aspects of phenomena we can experience. For the realist, such constructs possess a real existence even though they may not be experienced directly.[26] Moody (1951a, p. 190) pointed out that during the Middle Ages, the dispute between Averroes and Avempace was essentially one between empiricism and realism. Avempace considered it more reasonable to consider natural motion as that which took place without impediments while "to define the natural as that which never happens, seems to Averroes absurd" (Moody 1951a, p. 189). Avempace was asserting the reality of things which could never be experienced, while Averroes believed that such things were simply figments of the imagination.

Bunge (1966) criticised Mach's empiricist attempt to eliminate metaphysics from mechanics by eliminating concepts of force and mass and argued that metaphysics was an inevitable component of mechanics.

3.3.2.4 The Role of Observation and Experiment

Aristotle was a keen observer of nature and sought to explain natural phenomena in terms of self-evident truths and conclusions derived from them by a series of widely accepted forms of argument. The empirical base on which his understanding rested was those actual experiences we become aware of through our senses, and this understanding greatly influenced the medieval thinkers who followed Aristotle.

Galileo on the other hand modified what naturally occurred by designing experiments in which the natural impediments (as far as he was aware of them)

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[24] Hanson (1963) pointed out that it is impossible to consider the motion of an isolated body without a fixed reference frame and, for this, one needs the existence of at least one other body. However, as soon as this second body is introduced, the first is no longer isolated so that it appears that Newton's first law refers to an impossible state of affairs.

[25] The device known as Newton's cradle provides another example of illegitimate idealisation (Gauld 2006; Hutzler et al. 2004).

[26] Matthews (1994, pp. 163–74) has given a number of examples of contemporaries who were on opposite sides of this divide.

were reduced as far as possible or else dealt with in some other way (Koertge 1977; Segré 1980). Thus, through his inclined plane experiments, he was able to conclude that if all the impediments were removed, free fall motion would be uniformly accelerated.[27]

Newton operated in much the same way as Galileo, and from his three axioms and eight definitions was developed a deductive system describing the way things would move if those axioms were true. In Book 1 of his *Principia*, there are no experiments in the Galilean sense but he did provide some empirical evidence to support his third axiom or law. In Book 3 Newton showed that his conclusions deduced in Book 1 explained phenomena in our solar system. In Book 2 Newton carried out experiments into the resistance which various mediums presented to moving bodies and dealt with discrepancies between his results and his expectations in a rather cavalier manner having more confidence in his theory than in his results (Gauld 2009, 2010).

3.3.3 Frontier Science

Science is often taught as a completed self-consistent body of knowledge supported by evidence from demonstrations or experiments, and science is seen as this final, fully justified body of knowledge found by the use of methods appropriate to activities labelled as "scientific". The focus in teaching is on the final product of the process of scientific thought such as the expositions found in Galileo's *Discourses* or Newton's *Principia* or in most modern-day mechanics textbooks. In fact, publications such as these are generally all that are available for the teacher.

However, if one focuses not on this body of knowledge but on the processes which have led to its formation, the activity labelled "scientific" becomes much messier. The history of mechanics demonstrates clearly the unruliness of this process, and the study of laboratory worksheets, notebooks and correspondence such as those of Galileo[28] and Newton[29] shows very clearly something of the processes of thought which led up to that body of knowledge. This "frontier science" is part of the scientific process along with the dead ends and side tracks which accompany it. In Book 2 on his *Principia*, Newton explored new areas in

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[27] It is interesting to note that in the discussion which took place on day 4 of *Discourses,* Galileo dealt with two-dimensional trajectory motion but presented no experimental data although it was evident from his working papers that he had carried out a series of experiments to show the parabolic nature of these trajectories. While he tried as far as possible to reduce impediments, he was not aware of the effect of rotation on the acceleration of a rolling ball and no doubt noticed the rather significant discrepancies between his results in his unpublished working papers and what he expected to find (see Sect. 3.5.3.2).

[28] Galileo's working papers can be viewed at the website: http://mpiwg-berlin.mpg.de/Galileo_Prototype/index.htm.

[29] See Hall and Tilling (1975–1977), Herival (1965), Scott (1967), Turnbull (1959–1961), and Whiteside (1967–1981).

which to apply his theory and often (especially in his fluid mechanics) moved along on the basis of assumptions with little foundation.[30] Such procedures show how scientific knowledge often emerges from ignorance, error, adherence to particular world views, the absence of appropriate equipment and the lack of adequate analytical tools.

The works of Drake,[31] Hill (1979, 1988), Lindberg (1965), MacLachlan (1976), Naylor,[32] Segré (1980), and Settle (1961) on attempting to make sense of the worksheets of Galileo and of Herival (1965) and Westfall (1971) on interpreting Newton's notebooks and correspondence show something of the difficulties in these processes but also open up the rich world of the human endeavour of scientific discovery. It also reveals more clearly than most textbooks do the tentative nature of scientific knowledge.

3.3.4 Mechanics and Technology

There has been a close link between science (concerned with explanations) and technology (concerned with know-how) throughout history although it has never been a one-way relationship (Price and Cross 1997). While it is true that the development of science has led to new technological devices and processes, it has also been the case that technology has often developed independently of science and has led to new areas of scientific investigation. For example, simple machines like the lever and the inclined plane have been known since antiquity but were central to the investigations of Galileo into motion. The needs of navigation stimulated the search for more and more accurate clocks (Matthews 2000, Chap. 2), and military technology led to increased interest in the motion of projectiles. This shows clearly the way in which science influences and, in turn, is influenced by society.

3.4 History of Mechanics and Student Conceptions

A great deal of research has been carried out into the conceptions which people possess and which relate to mechanics.[33] One of the main findings of this research is that many people possess the concept found in Aristotle that motion requires a mover. As a result a body not experiencing the action of a force will be at rest.

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[30] See Gauld (2010), Herival (1965), Smith (2001), and Westfall (1971).

[31] See Drake (1973, 1974, 1975a, b, 1978, 1990).

[32] See Naylor (1974a, b, 1976, 1977, 1980, 1983).

[33] See, for example, Brown (1989), Clement (1982), Doménech et al. (1993), Galili and Bar (1992), Gunstone (1984), Halloun and Hestenes (1985), Ioannides and Vosniadou (2002), Lythcott (1985), McCloskey (1983), Montanero et al. (1995), Steinberg et al. (1990), Twigger et al. (1994), Viennot (1979), and Whitaker (1983).

In many cases people believe that, when a projectile is thrown, a force is imparted to it by the thrower which enables it to move after it has left the hand of the thrower. In the case of collisions, this notion transfers to the view that the body which has the greatest value of mv exerts the greatest force so that the forces exerted by the two bodies on each other are not equal (as they are in Newton's third law) but depend on the mass and speed of the bodies.

It has been pointed out that this concept of force is very like that held by Buridan and Piaget and Garcia (1989, pp. 30–87) argued that the development of the conception of force in young people follows very much the same path as that in the history of mechanics between the times of Aristotle and Newton.[34] This has suggested to many science educators that reference to the way in which the history of mechanics progressed may assist teachers in encouraging students to make the transition to more developed concepts such as those advocated by Newton.

However, it must be acknowledged that the contexts in which students and early physicists work are vastly different (Gauld 1991). Physicists possess a wider range of skills and interests relevant to their work than modern students. They consciously pursue understanding as they solve problems which arise for them in the process of increasingly articulating and discussing these problems and solutions with one another. On the other hand, until they are asked by an educational researcher, the modern student may probably never have consciously considered the question of the nature of force except in so far as they are taught about it in school.

In spite of the possible differences in meaning between statements of students and statements of early scientists about motion and force (cf. Sect. 3.3.2.1), there is still sufficient similarity to expect that history might supply resources which are able to make more plausible those concepts which are to be taught but which students find difficult to accept.

3.5 Some Historical Resources for Teaching Mechanics

Four potential resources from history to help students learn about the nature of science or to understand those concepts important in mechanics are discussed in what follows. These are (a) explanations and illustrations, (b) thought experiments, (c) experiments, instruments and technological devices and (d) anecdotes, vignettes and stories.

3.5.1 Explanations and Illustrations

History provides a source of explanations and illustrations which may assist present-day students to understand those things which they find difficult. Posner and his colleagues (1982) argued that, for a student to accept what the teacher is communicating,

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[34] See also Eckstein (1997), Nersessian and Resnick (1989), and Ioannides and Vosniadou (2002).

the student must at least find what is being said to be plausible. It must make some sense whether or not the student at first believes it to be the case. The intellectual environment of the past in which problems closer to the everyday experiences of the student were being investigated could be a source of alternative explanations to those in the textbook or provided by the teacher.

One simple example is with common misunderstandings of Newton's third law which is often stated as: "To every action there is an equal and opposite reaction". This gives no indication about the meaning of action and reaction and many students, for example, regard the weight of a book resting on a table and the force of the table on the book to be the action and reaction of Newton's third law. Thus the students link Newton's law with equilibrium. Newton himself stated the law in another, more helpful and less misleading, way: "The mutual actions of two bodies upon each other are always equal, and directed to contrary parts". This directs attention to the role of the two bodies and their actions on each other.

Because of their belief that the force of a moving body is determined by its speed and its mass, students have difficulty in believing that the forces between two colliding bodies are equal as Newton's third law of motion states. This belief was prevalent up to and beyond the time of Newton, and there were many attempts by Newton and those who promoted his system to render this law more plausible with detailed explanations and illustrations. Gauld (1998a, b) has discussed many of these contributions and shown that they often demonstrated that the third law of motion followed from ideas which were presumed to be self-evident (or at least accepted by the audience).

For example, Mach (1893/1960, pp. 247–8) developed an illustration the purpose of which was to make Newton's third law more plausible. His starting point was the self-evident truth that if one of two identical bodies, A and B, exerted a force, F, on the other then, because of symmetry, the second would exert an equal and opposite force, $-F$, on the first. Imagine now that there were three identical bodies, A, B and C and that B and C were combined to make a body, D, with twice the size and mass of A. The force experienced by A would now be $2F$ because B and C in body D would both exert forces equal to F on it. The force on the body D would now be $-2F$ because A would exert a force equal to F on each of B and C. This argument can be extended to explain why Newton's third law applies to bodies of unequal mass but each made up of a number of different identical bodies, but it is not so easy to extend it to bodies which are not identical since the necessary symmetry no longer exists.

3.5.2 Thought Experiments

Another way in which new ideas have been made more plausible in the early history of mechanics has been to use thought experiments. Procedures are carried out in thought which would normally be difficult or impossible to carry out in actual practice, and the audience is led from some generally accepted premise to a previously unknown or unexpected conclusion.[35] It is probable that such thought experiments could serve a similar role in today's classrooms (Matthews 1994, pp. 99–105). A number of thought experiments relating to mechanics are discussed.[36]

3.5.2.1 Galileo and the Speed of Falling Bodies

One of Galileo's older contemporaries, Giovanni Benedetti (1530–1590), had proposed a thought experiment to show that two bodies of different weight but the same density would fall in a vacuum with the same speed (Dijksterhuis 1961, p. 269). Everyone agreed that two bodies of equal size and density would fall together to the earth. If they were loosely tied together with a string they would therefore exert no force on the string. Thus they could equally be joined so that they form one body, now of twice the weight, which should therefore fall with the same speed as the two tied loosely.

Galileo modified this thought experiment to involve two bodies of different densities and different weights (*Discourses*, pp. 66–7). According to Aristotle the heavier would fall with a greater speed than the lighter. If the two were tied together with a string, the heavier one would pull the lighter one down so that its speed increased, while the lighter one would pull the heavier one up so that its speed decreased. Thus the speed of the two would be somewhere between the speeds of the two separately. However, the combined body, according to Aristotle, should fall with a speed proportional to its weight and so travel faster than the heavier of the two. Thus, Galileo claimed to demonstrate that Aristotle's conclusion was invalid.

3.5.2.2 Stevin and the Inclined Plane

Another of Galileo's older contemporaries, Simon Stevin (1548–1620), presented a thought experiment in which a body resting on an inclined plane was connected by a string passing over a pulley to a body hanging vertically. Of interest to Stevin and his contemporaries was the relationship between the weights of these two bodies when they were at rest (Dijksterhuis 1961, pp. 326–7). Stevin imagined a long chain loop hung motionless over a frictionless inclined plane so that part of it draped the vertical section, part of it draped the inclined section and the rest hung in curve below the plane (see Fig. 3.3). He argued that the part of the chain below the plane hung symmetrically and so exerted equal forces on the other two parts. In fact it

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[35] See Galili (2009), Gendler (1998), and Helm and Gilbert (1985). Of course the truth of the outcome of a thought experiment depends on the truth of the premise.

[36] Other thought experiments not discussed here include Galileo's use of two inclined planes to show that an unimpeded moving body would continue to move with undiminished speed on a "horizontal plane" around the earth (see *Dialogue*, pp. 145–8) and Archimedes', Galileo's and Mach's thought experiment to establish the principle of the lever (Galileo, *Discourses*, pp. 109–12; Goe 1972; Mach 1893/1960, pp. 13–8).

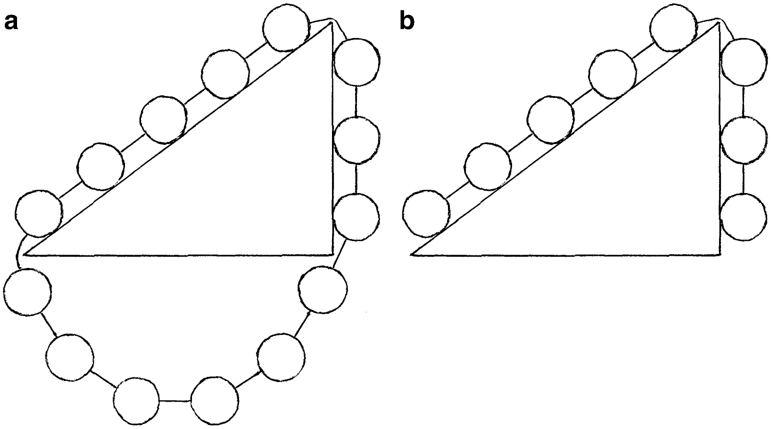

Fig. 3.3 Stevin's thought experiment to compare effective weights of bodies on an inclined plane

could be removed without disturbing the balance of the chain. The other two parts therefore balanced each other. Since the weight per unit length of the chain was constant, the weights of these two parts were therefore proportional to their lengths, that is, to the lengths of the incline and the vertical section, respectively. Thus a vertically hanging weight would balance a larger weight on the incline in the same proportion that the length of the incline is larger than the vertical height.[37]

3.5.3 *Experiments, Instruments and Technological Devices*

In the early history of science, equipment and experiments were much simpler and so provide a source of activities for use in classrooms which can help students deal with some of the problems they experience with the concepts they are learning. Many of the historical experiments have been used both to understand in more detail what the early scientists achieved and also to assist present-day students to understand the concepts which those scientists developed. A few well-known experiments are considered below, but many others, suitable for classroom use, can be found in the historical and educational literature.[38]

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[37] Another possibility for Stevin's arrangement is that the chain moves from one state to another identical state and so keeps moving forever. Stevin ruled this out because he denied that perpetual motion was possible. Of course, perpetual motion is impossible because energy is dissipated through friction, but in Stevin's arrangement friction is necessarily absent.

[38] These include the investigation of the motion of the simple pendulum (MacLachlan 1976; Matthews 2000, pp. 245–8), the use of Escriche's inclined pendulum to vary the effective value of the acceleration due to gravity (Vaquero and Gallego 2000; Mach 1893/1960, pp. 207–9) and experiments based on Newton's investigation of the resistance to motion of air and water (Gauld 2009, 2010). Blair (2001) and O'Connell (2001) encourage the use of ancient technological devices as aids in teaching about motion in the classroom.

3.5.3.1 The Inclined Plane Experiment

A number of people have carried out replications of Galileo's experiment with inclined planes.[39] Drake and Settle provided detailed accounts of Galileo's possible procedure (Drake 1990, pp. 9–15; Settle 1961) and, while some speculation about the finer details was required, the basic outline was Galileo's own (*Discourses,* pp. 169–70). The purposes of these investigations have differed. For some (e.g. Settle 1961; Drake 1973), it was to determine whether Galileo could actually have carried out the experiment with the equipment which he had and with the accuracy he claimed. For others it was as an exercise for students who were learning about motion with an eye to its history (Straulino 2008; Erlichson 1997a; Sherman 1974).

Drake (1975b, 1990) claimed that in the first instance, Galileo may have used the regular metre of a song to arrange markers across the plane so that, as the ball rolled over each marker, it gave an audible click which coincided with the beats of the song. The distance between markers would then be in the ratio of 1, 3, 5, 7, 9 and so on.

The more normal procedure is to use a large can of water which is allowed to flow through a small bore pipe (*Discourses*, p. 170). The end of the pipe is uncovered at the beginning of the required time interval and covered up at the end. The mass of water is the measure of the size of the time interval (Settle 1961; Drake 1973).[40]

3.5.3.2 The Parabolic Path of Trajectories and the Law of Free Fall

Galileo accepted the notion that the horizontal motion of a trajectory continued at a constant speed, while the vertical motion was accelerated uniformly. These two motions were independent of each other.

His experiments to determine the shape of the trajectory were described and replicated by Drake (1990, pp. 109–15), Naylor[41] and Teichmann (1999). A ball was allowed to run down an inclined plane towards the top of a table. At the end of the plane, a small curve allowed the ball to be projected horizontally so that it then travelled along a curved path to the floor. If the ball always began from the same vertical height, H, above the table, it would leave the top of the table with the same speed, S. The horizontal range, D, from the point of projection was measured by observing the point of impact on the floor. Galileo believed (correctly) that the speed at the bottom of the incline was proportional to the square root of the vertical height from which the ball began. Because this horizontal speed was maintained as the ball moved from the end of the incline to the floor, the range was proportional to S. By using various values of H, Galileo was able to show that D was proportional to $\sqrt{(H)}$.[42]

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[39] See Drake (1973, 1990, pp. 9–15), MacLachlan (1976), Naylor (1974b), Settle (1961), Sherman (1974), and Straulino (2008).

[40] Use of this method in a classroom is shown on the website http://www.youtube.com/watch?v=ZUgYcbBi46w.

[41] See Naylor (1974b, 1976, 1980, 1983).

[42] The problem Galileo apparently encountered with this experiment was that when H was equal to the height of the table on which the inclined plane was situated, he expected that D would equal $2H$.

3.5.3.3 Newton's Colliding Pendulums

To illustrate his third law, Newton described a series of experiments in which pendulum bobs collided. He used a property of the pendulum well known to Galileo and to Newton's contemporaries, namely, that the speed at the bottom of the swing was proportional to the length of the chord from its starting point to the bottom point (Erlichson 2001; Gauld 1998a, 1999). For a long pendulum with a small amplitude, this means that the speed at the bottom was almost proportional to the distance it was pulled back before the bob was released.

Bifilar pendulums allow the pendulum to swing in only one plane and with two such pendulums the speed of the bobs for two colliding bodies can easily be controlled by the distance they are initially pulled back. Using bob masses and speeds which are in simple ratios, the application of Newton's third law in a dynamic context can easily be explored in the classroom.

3.5.4 Anecdotes, Vignettes and Stories

Many textbooks contain small inclusions in which the history of science is acknowledged (Shrigley and Koballa 1989). These are often there simply to lighten up what is the more serious development of the concepts being taught or to provide some relief from what is often considered to be the boring stuff of science teaching. However, when used in this way and by teachers who are not historians of science, the history often becomes distorted and the only purpose is to provide motivation to the students in their learning of scientific concepts (Gauld 1977; Whitaker 1979a, b). The historical integrity of the accounts is often lost. Wandersee (1990) has explored the more systematic use of small-scale historical vignettes in science lessons and has demonstrated their effectiveness (especially as far as fostering interest is concerned) when used with some topics. Klassen (2009) outlined the nature of stories in teaching science and has described how they should be developed from knowledge of the historical context in which they are set.[43]

Stinner and his colleagues[44] emphasised the importance of the role of large-scale contexts in teaching the story of mechanics. This provides students with the opportunity of becoming familiar with the overall structure of thought of a period and with the way in which investigation of motion was embedded in this context. In this way, for example, the difference between the Aristotelian, Galilean and Newtonian frameworks can be pointed out to students and the nature of progress in science – both in methodology and concepts – be better appreciated by them (Rosenblatt 2011).

Instead, his value for D was only 80% of what he expected. Today we can account for this discrepancy by appealing to the rotational kinetic energy of the ball which reduces D to 5/7 (or 85%) of Galileo's expected value.

[43] Nersessian (1992, p. 71) suggested that one of the reasons for the success of thought experiments is that they are set in an attractive narrative context.

[44] See, for example, Stinner (1989, 1990, 1994, 1995, 1996, 2001) and Stinner and Williams (1993).

Two stories related to the history of mechanics and often found in physics textbooks are those concerning the claim that Galileo defeated his Aristotelian opponents with his experiment from the Leaning Tower of Pisa and the claim that Newton's conception of universal gravitation arose from his observation of a falling apple.

3.5.4.1 Galileo and the Leaning Tower of Pisa

In 1935 Lane Cooper concluded that the story of Galileo confounding the Aristotelians of his day by dropping bodies of different weights from the top of the Leaning Tower of Pisa was untrue. This conclusion was based on the fact that the various versions of the story contained discrepancies. The original account was by Viviani, one of Galileo's students, who was known to be unreliable in some aspects of his account of Galileo's life. Cooper also based it on what was known of Galileo's views of falling bodies at that time and of the views of the Aristotelians. Aristotle believed that the speed of falling bodies was proportional to their weight, while Galileo, when in Pisa, believed that their speed was proportional to their densities. Thus, for Aristotle heavier bodies always fell faster than lighter bodies, while, for Galileo, bodies with the same density fell at the same speed although bodies of different densities fell with different speeds.[45]

Cooper's third argument was that nowhere in Galileo's writing does he refer to this experiment even though it was deemed to be so devastating a rebuttal of Aristotle's position. In addition, Galileo's opponents are silent about the apparent damage Galileo did to their case.

However, Drake (1978, pp. 18–21; 413–6) expressed a different opinion of the veracity of the experiment and believed that it might have occurred, not "in the presence of all the other teachers and philosophers, and the whole assembly of students" as Viviani claimed (Cooper 1935, p. 26) but in the presence of Galileo's own students at Pisa.

This lack of consensus about the story provides some incentive for students to investigate the likelihood of both views based on a consideration of the views of Galileo and his opponents at the time.[46]

3.5.4.2 Newton and the Falling Apple

This well-known story which claims that Newton's law of universal gravitation was discovered when an apple fell on his head as he sat under an apple tree is usually written off as untrue. However, McKie and de Beer (1951–2a, b) traced the ancestry of the story to two sources during the last year of Newton's life and to Newton

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[45] See Adler and Coulter (1978) and Moody (1951a, b); for an alternative reconstruction, see Franklin (1979).

[46] A re-enactment of this story can be seen at the website http://youtube.com/watch?v=_Kv-U5tjNCY. The discussion by Erlichson (1993) is also helpful in considering the truth of this story.

himself. However, one might ask, if true, what does the story tell us of importance about Newton's thought? Westfall (1993, pp. 51–2) claimed that

> the story vulgarizes universal gravitation by treating it as a bright idea. A bright idea cannot shape a scientific tradition … Universal gravitation did not yield to Newton at his first effort. He hesitated and floundered, baffled for the moment by overwhelming complexities, which were enough in mechanics alone and were multiplied sevenfold by the total context.

Westfall's point about the implications of the usual telling of the story was that, from the evidence provided by his notebooks, the development of Newton's idea of universal gravitation was much more protracted than the story suggests (see also Smith 1997).

3.6 Some Curriculum Examples

3.6.1 Mach and The Science of Mechanics

A pioneering work with the intention of teaching mechanics through its history was *The Science of Mechanics* by Ernst Mach (1893/1960). In this book Mach presented his view of how and why mechanics developed in the way it did, and he argued his claim that mechanics should be rightly conceived as the outcome of an empiricist methodology. In spite of its philosophical bias, this book is an accessible and a rich source of information about the historical context of mechanics, some of which has been cited in previous sections of this chapter.

3.6.2 Taylor and Physics: The Pioneer Science

In the twentieth century the textbook, *Physics: The Pioneer Science*, by Lloyd Taylor (1941) was a notable effort to bring the study of physics to a wider audience. Its table of contents reads like that of a conventional physics textbook "but the conventional subject matter, along with its mathematical treatment, has been embedded in a historical matrix" (Taylor 1941, p. vi). Chapters 1–18 are devoted to mechanics, and the concepts are developed with an eye to the issues of importance to those involved in its history. Along with the treatment of the concepts of mechanics, Taylor interpolates comments on the nature of science and of the position on these matters taken by the historical figures he appeals to.

3.6.3 Holton and His Legacy

From the early 1950s to the present, Gerald Holton promoted the use of history to teach physics in widely used textbooks[47] and especially in the *Project Physics* course (Holton et al. 1970).

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[47] See Holton (1952), Holton and Brush (2001), and Holton and Roller (1958).

In Holton and Roller's book, *Foundations of Modern Physical Science*, Chaps. 1–18 deal with mechanics (including planetary motion). The table of contents in this book is somewhat different to that of Taylor's in that some of the chapters have a specifically historical (e.g. Chap. 2: "Galileo and the kinematics of free fall") or philosophical (e.g. Chap. 8: "On the nature of scientific theory") focus. Section IV (Chaps. 13–15) is concerned with "structure and method in physical theory".

The *Project Physics* course was based on similar principles to those guiding textbooks of Holton and his colleagues but, in addition, contained a great deal of additional material to assist the teacher. The course was presented in six separate units of which two, *Concepts of Motion* and *The Triumph of Mechanics*, were related to the focus of this chapter. Historical information and practical activities were included, and each unit was accompanied by a reader which contained other writings relevant to the topic of the unit. The course was widely adapted for use in other countries and was recently updated.[48]

3.6.4 Contextual Teaching and Curriculum Structure in Mechanics

In the texts discussed above, what goes on in the classroom is determined largely by the written material provided by the teacher. However, there is considerable evidence that students often end up learning a series of "facts" which make little sense to them beyond the classroom because of the alternative conceptions which they more strongly adhere to and because they are not being taught in a credible way how scientific knowledge has been gained and justified. As a result many argue that a new approach is long overdue.[49] The case made by such educators is that students will learn science better by subjecting their own ideas and those they are being taught to greater scrutiny in order to understand better the origins of scientific knowledge, the way this knowledge has changed and the reasons for these changes. In this enterprise the history of science has a major role to play.

The story of the development of mechanics begins, both for Aristotle and for present-day students, with the idea that all motion requires a mover. Students will therefore be expected to have problems, as Aristotle did, with understanding why, for example, projectiles continue to move after contact with their mover is broken. Without consciously arguing the case, students today often adopt a version of the medieval impetus solution to this problem. Respect for the ideas of students links what they are learning with where the students are at present, while respect for the history of science relates these ideas to the wider context of science itself. In this way, at least in the area of mechanics, students are able to see that ideas somewhat like their own have been held by well-known scientists, and therefore efforts to understand why they changed (or need to be changed) are encouraged.

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[48] See Cassidy et al. (2002); see also Holton (2003).

[49] For example, Arons (1988); Galili (2012); Monk and Osborne (1997); Rosenblatt (2011); Stinner (1989, 1994, 1995).

3.7 Teaching Mechanics in the Science Education Research Literature

Contributions from the science education research literature are many and varied and include (a) presentations of periods of history or analyses of historical development of particular areas of mechanics without any reference to their use in the classroom, (b) such analyses accompanied by suggestions about their potential use for teaching mechanics, (c) more explicit advice about how a particular event or sequence of events in history could overcome problems in teaching mechanics, (d) descriptions of programmes used for teaching a particular topic in mechanics using history and (e) evaluations of courses which have employed a historical approach to teaching mechanics.

Over a 20-year period, 105 papers dealing with the history of mechanics were published in nine science education journals,[50] and of these 26 made no explicit reference to classroom matters (e.g. see Hecht 2003). Of the 79 papers which do discuss the relevance of the history for the classroom, most of these discussions are brief.[51]

On the other hand, the whole of Stinner's (1994) outline of the history of force from Aristotle to Einstein was presented in a form specifically designed to be used by teachers. Espinoza's (2005) survey of ideas about motion and force both throughout history and in the thought of modern-day students was published with the express purpose of helping students overcome conceptual problems which they apparently shared with early scientists. Possible aids in overcoming widespread difficulties in understanding and accepting Newton's third law were presented by Gauld (1998b) who assembled the approaches used by Newton and those who followed him to render this law more plausible to those attempting to learn it. In order to demonstrate the effect of varying the acceleration due to gravity on the period of the pendulum, Vaquero and Gallego (2000) recommended the use of Escriche's pendulum (invented in 1876) in which the plane of oscillation of the pendulum can be varied to change the size of the force responsible for the oscillation without changing the mass of the bob (see also Mach 1893/1960, pp. 207–8).

In only 16 papers is reference made of actual classroom implementation. There have been complete courses in which the study of motion is taught both to demonstrate the way in which science progresses and to help students understand the concepts involved. Erlichson (1997a, 1999a, b, 2001) described a course for nonscience majors called "Galileo to Newton and Beyond" in which the students repeated historical experiments (including Galileo's inclined plane and pendulum experiments and elastic collision experiments when dealing with Huygens) and discussed the development of concepts of motion in the seventeenth century.

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[50] Journals included in the analysis were *American Journal of Physics* (17)*, International Journal of Science Education* (4)*, Journal of Research in Science Teaching* (1)*, Physics Education* (16)*, Research in Science Education* (3)*, Science & Education* (41)*, Science Education* (0)*, The Physics Teacher* (20) and *The Science Teacher* (2). The period covered was 1992–2011 and the number of articles in each journal is shown in parentheses.

[51] See, for example, Galili and Tzeitlin (2003) and Wörmer (2007).

The students also discussed the implications of some of the propositions in Galileo's *Discourses* and Book I of Newton's *Principia*. Many of Erlichson's papers in physics teaching journals (for example Erlichson 1997b, 1999b, 2001) serve to provide background to such courses as this. Fowler (2003) briefly described a similar course called "Galileo to Einstein". Stinner and his colleagues[52] proposed an approach to teaching mechanics which takes seriously the context within which questions are asked. One of their contexts is history, and awareness of this enables choices to be made about how information from the history of mechanics can be employed in the classroom. Teichmann (1999) described how he used one of Galileo's working manuscripts (*f.*116*v* apparently containing diagrams and the results of theoretical calculations and experimental results for Galileo's trajectory experiments) with physics teachers attending in-service courses at the Deutsches Museum in Munich. This enabled them to investigate the meaning of the symbols on the page and to attempt to understand the possible process of Galileo's thinking.

Within the group of publications in science education journals over the last 20 years, there have been only six in which evaluations of courses designed to use history to teach mechanics are reported (although some of these evaluations are only informal). In some cases[53] these reports have been very cursory, while in other cases[54] the reports are much more comprehensive. Seker and Welsh (2006) investigated the teaching of two units on motion and on force with the specific purpose of addressing three different aims for using physics history, namely, learning of concepts, learning about the nature of science and development of interest. They devised three different instructional procedures each of which was designed to address a different aim along with a traditional procedure in which history played no part. They showed that in all classes students improved in their understanding of the concepts involved, that use of stories did improve some aspects of interest, that certain features of the nature of science improved and that there were differences in the outcomes in these areas for the two units. This last result suggests that using history might produce different outcomes depending on the topic which is being taught.

3.8 The Next Step

A survey of the literature shows that there is a great deal of information about the history of mechanics in historical, philosophical and science educational publications. However, before it substantially influences the teaching of mechanics, three problems must be overcome: teachers have to be convinced that changing their approach to teaching mechanics by introducing more history has advantages for them and their students; the material must be translated into a form which is more

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[52] See Stinner (1989, 1994, 1995, 2001).

[53] See, for example, Kokkotas et al. (2009), Kubli (1999), and Teichmann (1999).

[54] See Kalman and Aulls (2003) and Seker and Welsh (2006).

easily accessible to teachers; and the effectiveness of using these resources needs to be clearly demonstrated through well-designed evaluations.

3.8.1 Teacher Use of Historical Curriculum Resources

The focus in secondary school physics is generally on the concepts of physics, and the main roles of the history of mechanics are in assisting in the teaching of these concepts and, often to a lesser extent, helping the student to understand something of the nature of science (see Wandersee 1990).[55]

Because of this focus on the teaching of science concepts, the task of encouraging teachers of mechanics to introduce historical material is not an easy one (Monk and Osborne 1997). Typical of the attitude of many physics teachers is that of Paul Hewitt, a widely respected US secondary school physics teacher, who complained:

> that time spent on the 17th-century physics of Galileo is time not spent on the physics of Newton, Kepler, Pascal, Joule, Kelvin, Faraday, Ampere, Coulomb, Ohm, Maxwell, Huygens, Bohr, Planck, Einstein, de Broglie, Heisenberg, Rutherford, Curie, Fermi, Feynman and others. (2003)

Monk and Osborne (1997) argued that the constraint of the focus on teaching concepts should be a major factor in the design of programmes which take into account the history of science and they suggested that neglect of this factor has been the reason why many suggestions about using history in teaching physics have not been implemented. They caution against moving too rapidly but advocate a historical approach to selected units. They propose the presentation of the history as a story with all those features which make storytelling motivational.[56]

3.8.2 Historical Resources for Teaching Mechanics

Much of the information about the history of mechanics is spread rather thinly through the literature, and a great deal of it is in technical, historical or philosophical journals. Because these publications are not primarily concerned with educational implications, the material is often unsuitable for use by teachers in the classrooms. Even where historical information appears in science education journals and is accompanied by advice about classroom use, teachers would still have to work hard to adapt it in appropriate ways.

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[55] There are, of course, more sophisticated contexts in which the history of mechanics can be used such as in tertiary courses on the history of science, but the greatest exposure to mechanics occurs in the secondary school whether for future specialists of physics or for science for non-specialists.

[56] See also Arons (1988), Rosenblatt (2011, Chap. 6), Stinner (1994), and Stinner and Williams (1993).

Teacher specialties tend to be in their science area and not in history or philosophy, and many of the incidental historical or philosophical contributions of physics textbook are often unsatisfactory. Apart from resources which accompany a fully developed course such as *Project Physics* or those designed by Erlichson (1997a) or Fowler (2003), there is little that is available in a form which teachers could use with only a reasonable effort to incorporate it into their teaching programmes. A collection similar to that produced by Sutton (1938) or Meiners (1970) for physics demonstrations would make a useful beginning.

3.8.3 Evaluation of Programmes Which Use Historical Material

A number of claims have been made about the value of using historical material in the mechanics classroom. Most frequently these refer to the use of history not for its intrinsic value in informing mechanics students about the development of their subject but for the role of history in motivating students, helping them to understand better the concepts of mechanics or developing students' appreciation of the nature of science.

While there are many (mainly informal) suggestions about the value of a particular historical presentation in the teaching of mechanics, there have been very few serious attempts at evaluation to see whether these suggestions possess any substance. Comprehensive evaluation of the *Project Physics* course was carried out (Welch 1973), but since the 1970s the only published report in the area of mechanics is that by Seker and Welsh (2006). Research is needed to establish clearly the characteristics of effective programmes in which history is used to teach mechanics.

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Chapter 4
Teaching Optics: A Historico-Philosophical Perspective

Igal Galili

4.1 Introduction

This chapter reviews the attempts to include the history and philosophy of science (HPS) in the teaching of light and vision and the lessons learned from these attempts. This kind of curricular innovation requires special effort and draws on extensive research in learning theory and cognitive psychology and culturology, all applied to a science curriculum on light.

Light is traditionally seen in science as one of the two entities that comprise physical reality: light and matter. The dichotomy stems from the difference between photons and other elementary particles, which possess mass. Our scientific knowledge of light is organized in the form of the *Theory of Light* – Optics.[1] The history of science provides an astonishing story of transformations of this knowledge through different periods and levels of complexity, before the appearance of the modern theory of light and matter. This history can be represented as a discourse of theories in which a certain theory dominated during each period (Fig. 4.1).

Within the liberal tradition of science education, the major question is how to represent this knowledge in order to give the students an inclusive and essentially representative big picture of human knowledge about light. As part of this effort, it is important to identify significant periods of knowledge transformation regarding light and in this way create a structure to be addressed in the course of learning.

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[1] *Theory* is used here in the inclusive sense of a collection of knowledge elements about reality in a particular domain. A fundamental theory in physics includes principles, laws, concepts, models, experiments, problems, practical applications, apparatus, and other elements, all conforming to the same set of basic principles. The broad structure of this knowledge will be specified below.

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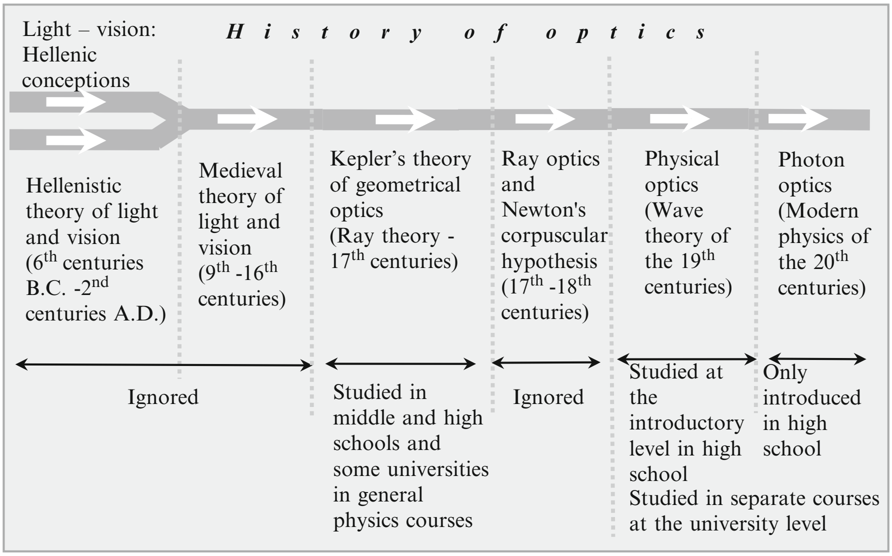

Fig. 4.1 The historical development of optical theories and their appearance in high school and university curricula

As seen in Fig. 4.1, some theories are not usually presented to students in regular physics courses. Moreover, the three parts of optics which are presented usually appear in isolated educational settings: (i) Geometrical Optics (the theory of rays), (ii) Physical Optics (the theory of waves), and (iii) Modern Optics (the theory of photons). The latter is often incorporated into modern physics courses. Optics contributes to physics education all the way to the university level, even if it is chopped into pieces along the way.

The history of science presents a big picture that unifies the various theories of light. This perspective includes the pre-theory conceptions of light and vision in the Hellenic period as well as the theory of rays developed during the Hellenistic, medieval European, and Muslim periods prior to the scientific revolution of the seventeenth century. Usually, teaching of optics does not include any developments prior to the ray theory of the 17th century and even then, Newton's color rays, Huygens' pressure waves, the particle-wave debate which led to the domination of Newton's conception of particles in the 18th century are scarcely mentioned.

I will now show how elements of HPS related to optics have been incorporated into teaching materials. First comes students' knowledge of light, followed by a discussion of the available resources of the history of optics. Next come the views regarding teaching the knowledge of optics and the nature of this scientific knowledge. The recently developed framework of the *cultural knowledge* of optics is then reviewed, framing the contribution of HPS to the teaching of science.

4.2 Studies of Students' Knowledge of Optics

Educational constructivism (e.g., Duit et al. 2005) sees students' knowledge of light and vision, before and after instruction, as being of great importance. Numerous students' conceptions in optical knowledge have been investigated and reported in an organized manner (e.g., Galili and Hazan 2000a). The abundance of misconceptions results from the counterintuitiveness of light theory and the process of seeing objects which requires a nonobvious explanation: a diverging light flux emanated from each point of the observed object converges inside the eye to a correspondent point on the retina. The image created in this way is then interpreted by the mind. This conception is usually replaced by "commonsense" ideas, while the process described in theoretical terms is not actually what one can "see." Scientific knowledge in the area of optics as developed by scholars can be seen as a puzzle resolved over hundreds of years.

Here are some aspects of the complexity. The "passive" nature of vision – its intermissive character – is not obvious. The observer *receives* light, but the impact of single photons on the retina is never perceived. Only the impact of many photons can start a faint visual perception, making vision continuous. Visual perception is analyzed unconsciously and "informs" us that light is static and fills space, that it can be observed "from aside" as an object rather than an event or process.

The speed of light is enormous and never perceived as finite; it seems that light expands instantly the moment we press the switch. The wavelength of light is much shorter than that of any water wave, and thus the wave nature of light was revealed only through delicate experiments showing tiny deviations of light rays from straight paths. The obscure nature of light led to speculations, some of which were extremely inventive (Aristotle), which scientists used to describe and explain the phenomena of light prior to the presently adopted accounts. It is thus natural to realize that people spontaneously produce alternatives to the scientific account.

Researches who have revealed and documented students' conceptions and views on light and vision usually share the epistemologies of educational constructivism (e.g., Driver and Bell 1986) and cognitive psychology (Ausubel 1968). Numerous studies have shown that students' conceptions of light and vision show a certain consistency and similarity across educational and cultural backgrounds.[2] This universality indicates the "objective" origin of naïve knowledge, which is stronger than differences of psychological, social, ethnic, educational, and curricular factors.

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[2] See, for example, Andersson and Karrqvist (1983), Beaty (1987), Bendall et al. (1993), Bouwens (1987), Boyes and Stanisstreet (1991), Colin and Viennot (2001), Colin (2001), Feher and Rice (1988, 1992), Fetherstonhaugh et al. (1987), Fetherstonhaugh and Treagust (1992), Fleer (1996), Galili (1996), Galili et al. (1993), Goldberg and McDermott (1986, 1987), Guesne (1985), Jung (1981, 1982, 1987), La Rosa et al. (1984), Langley et al. (1997), Olivieri et al. (1988), Osborne et al. (1993), Perales et al. (1989), Ramadas and Driver (1989), Reiner et al. (1995), Reiner (1992), Rice and Feher (1987), Ronen and Eylon (1993), Saxena (1991), Schnepps and Sadler (1989), Segel and Cosgrove (1993), Selley (1996a, b), Singh and Butler (1990), Stead and Osborne (1980), and Watts (1985).

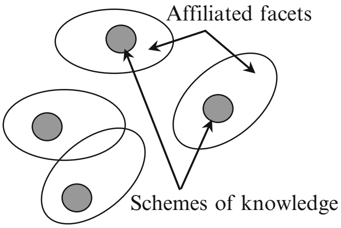

Fig. 4.2 Schematic representation of the Scheme-Facets-of-Knowledge structure of students' knowledge. The small circles designate schemes and the oval areas, clusters of affiliated facets. Since the same facet may match more than one scheme, the clusters may overlap

The alternative conceptions of light phenomena were found at all levels, from kindergarten (e.g., Guesne 1985; Shapiro 1994) to Ph.D. graduates (e.g., Schnepps and Sadler 1989), teachers (e.g., Atwood and Atwood 1996) and even in textbooks (e.g., Beaty 1987).

The abundance of persistent misconceptions suggests consideration of the structure of students' knowledge and the changes this knowledge undergoes during the course of learning. Some researchers have suggested considering students' knowledge as alternative *theories* (McCloskey 1983) parallel to science, even if inferior in inclusiveness and coherency. diSessa (1993) introduced the inclusive mental constructs of *phenomenological primitives* (p-prims) and considered students' knowledge to be fragmented and governed by p-prims, "naïve sense of mechanism" (ibid.). For example, the p-prim "force as a continuous mover" suggests that each motion is affiliated with an agent (force) and is reminiscent of the account of "violent" motion in Aristotelian theory. Another cognitive construct, *facets-of-knowledge* (Minstrell 1992), describes students' reasoning and strategies in concrete physical situations. Facets represent stable conceptual, operational, and representative ideas and beliefs. For example, students may consider a mirror image to be an entity that leaves an object, travels to a mirror, and remains there, to be observed later by a viewer (Bendall et al. 1993).

Based on these perspectives, students' knowledge in optics has been organized in a two-level structure of Scheme-Facets-of-Knowledge (e.g., Galili and Lavrik 1998). A *scheme of knowledge* represents general concepts, certain mechanisms, and cause-effect relationships between physical factors, such as "Light is comprised of light rays" or "An image is transferred as a whole entity" (Galili and Hazan 2000a, b). *Schemes* manifest themselves in context-specific *facets*: concrete realizations of the correspondent schemes. For example, the Image Holistic Scheme is related to a cluster of facets each of which applies the same idea to the various contexts of vision, mirrors, lenses, pinholes, and prisms. In all these cases, an image moves and stays as a whole. This two-level theoretical approach reduces the multitude of conceptions to less numerous schemes with affiliated clusters of facets (Fig. 4.2).

4.3 Resources in the History of Optics

Together with mechanics and astronomy, optics is one of the oldest areas of scientific exploration. Its history goes back to the dawn of science and illustrates how human knowledge of nature evolved. Mechanics, astronomy, and optics address the reality experienced directly through sense perception. Other domains of physics address more hidden reality and draw on the established concepts of mechanics and optics.

For the purposes of education, text resources in the history of optics may be classified in the following way:

1. Texts on *the history of science*, usually addressing great variety of specific cases from the history of optics.[3]
2. In-depth monographs, studies and detailed investigations of the history of optics.[4]
3. Textbooks in optics sometimes provide a historical presentation of disciplinary knowledge.[5] However, unlike the previous groups, these texts often ignore alternative and currently abandoned concepts from the past of science.
4. Books providing a narrative history of optics, written for the general public (e.g., Park 1997). These authors face a special challenge: to remain conceptually valid without the formal mathematical account and present the ideas, laws, and concepts of optics qualitatively. As a result, these books can be used in a very limited way in schools. However, they remain a highly stimulating source to satisfy their readers' curiosity, interest, historical awareness, imagination, and intellectual desire – all of crucial importance in overcoming the barrier of formalism on the way to genuine comprehension.
5. Original treatises remain indispensible, although novices may have troubles to understand them unaided. Pioneers in optics often explained their claims and related them to previous knowledge, displaying the continuity of the disciplinary discourse. Despite their archaic notions, style, and worldview, the originals preserve their validity.[6] Some originals are available in sourcebooks such as Cohen and Drabkin (eds.) (1966) and Magie (ed.) (1969).

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[3] See, for example, Crombie (1959, 1990), Dijksterhuis (1986), Forbes and Dijksterhuis (1963), Gliozzi (1965), Lindberg (1992), Mason (1962), Pedersen and Phil (1974), Sambursky (1959), Steneck (1976), Whittaker (1960), and Wolf (1968).

[4] See, for example, Boyer (1987), Dijksterhuis (2004), Emmott (1961), Endry (1980), Gaukroger (1995), Hakfoort (1995), Herzberger (1966), Kipnis (1991), Lauginie (2012), Lindberg (1976, 1978, 1985, 2002), Middleton (1961, 1963), Rashed (2002), Ronchi (1970, 1991), Russell (2002), Sabra (1981, 1989, 2003), Sambursky (1958), Shapiro (1973, 1993), Smith (1996, 1999), and Westfall (1962, 1989).

[5] See, for example, Arons (1965), Galili and Hazan (2004, 2009), Kipnis (1992), Mach (1913/1926), Taylor (1941), and Hecht (1998).

[6] Important original texts in optics include Aristotle (1952), Bragg (1959), Descartes (1637/1965), 1998, Fresnel (1866), Goethe (1810), Huygens (1690/1912), Kepler (1610/2000), Newton (1671/1974, 1704/1952), Ross (2008), and Young (1804, 1807).

4.4 Perspectives on the Involvement of HPS in the Teaching of Optics

The major subject of this review is the teaching of optics through the use of HPS-based materials. The idea of the use of history in developing an understanding of science has been analyzed by different scholars. For instance, Collingwood categorically argued in his *The Idea of Nature*:

> I conclude that natural science as a form of thought exists and always has existed in a context of history, and depends on historical thought for its existence. From this I venture to infer that no one can understand natural science unless he understands history and that no one can answer the question what nature is unless he knows what history is. (Collingwood 1949, p. 177)

Matthews (1989, 1994, 2000) has refined this claim in the framework of modern perspectives on science teaching and has listed and discussed the advantages of using HPS to achieve that goal. Seroglou and Koumaras (2001) have provided a review of the research on this subject available at the time. The following presents the approaches to the use of HPS in teaching optics:

1. The first proponents of using the history of science in science education based their argument on the tradition of liberal education, that is, the value of broad scientific literacy, and provided historical reviews at the beginning of their monographs (e.g., Lagrange 1788; Mach 1913). Pedrotti and Pedrotti (1998) and Hecht (1998) did the same in modern optical textbooks. There is, however, a norm which distinguishes the history found in such reviews from that found in historical studies. The former only address the elements of "correct" knowledge (Type-A). For instance, there are the specular reflection of light and its refraction, investigated by the heroes of Hellenistic optics, Heron and Archimedes (Cohen and Drabkin 1966). Heron argued for mirror reflection using the principle of "minimal path" (ibid, p. 263); Archimedes treated the same phenomenon using the idea of light path reversibility (Russo 2004, p. 63; Kipnis 1992, p. 27). The restriction of the discussion to Type-A knowledge, however, makes Heron's consideration irrelevant. Heron argued that the infinite speed of rays did not allow any deviation from the minimum path. Similarly, when this treatment quotes Fermat's corrections of "minimal" to "extreme" (maximal or minimal) and replaced "distance" to "time" as more "correct" and in accordance with scientific knowledge, Fermat's motivation, the *intention of nature* seeking the "simplest way" (Ross 2008, p. vi), is ignored.[7]

   Type-A reconstructions of the history of science as a method of teaching optics have led to development of special curriculum units (e.g., Mihas 2008; Mihas and Andrealis 2005; Andreou and Raftopoulos 2011). Mihas (2008) and Mihas and Andrealis (2005) have reconstructed the experiments from the Hellenistic (Ptolemy) and medieval Islamic (Al-Haytham) periods. The authors supported their teaching by using computer simulations.

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[7] The restriction of discussions to Type-A knowledge may be connected to the positivist philosophy seemingly prevailing in science classes (e.g., Benson 1989). This approach, however, does not adequately present controversies in scientific discourse or the educational complexity in facing specific misconceptions.

Kipnis (1992) developed a special course of optics for science teachers employing selected historical experiments where he applied the *historical-investigative* method. In his course, Kipnis suggested reproducing historical experiments using apparatus similar to the historical ones. Students discussed the results of the experiments and were guided to the theoretical implications leading to the conceptions and laws of optics. His discursive pedagogy, which is reminiscent of Galilean discourses, is close to the modern idea of "guided discovery" as a method of knowledge construction. This approach has been described as enhancing students' and teachers' interest in science, developing their initiative and inventiveness, and providing them with insights into the process of doing science (Kipnis 1996, 1998).

However, the history of optics contains more than the elements described above; it possesses other elements, Type-B knowledge, knowledge which emerged and was later refuted, being replaced by more advanced accounts. This knowledge is often seen as irrelevant and undesirable in science classes (Galili and Hazan 2001), as "incorrect" ideas may be seen as confusing the students, who, being immature, are unable to resolve discrepancies in the subject matter. In this view, novices require definite, correct, and unequivocal information, so, even when educators do state:

> If I were endowed with dictatorial powers, I would require everyone receiving a degree in a scientific subject to know its history and to have read the classical papers relating to it. Historical knowledge is important because it stimulates creative thinking. (Herzberger 1966, p. 1383)

they may only address knowledge of a certain type. Ironically, however, the restriction to Type-A knowledge frequently found in popular books about science practically excludes a need for history in education. Indeed, the laws of reflection and refraction of light do not require reference to Heron, Archimedes, Fermat, or Descartes to grasp their meaning and application. Indeed, numerous textbooks in optics do not mention these heroes of optical history.

2. Another idea regarding the use of HPS in educational materials has appeared in connection to research in science education. Its roots stem from the idea of *recapitulation* (ontogeny recapitulates phylogeny) as applied to education. Piaget was among the early proponents of this view (Jardine 2006), which has been discussed in psychology in the past (Kofka 1925). Leaving aside the presently rejected extreme – "*every* individual passes through *all* the stages of collective development" – certain fundamental ideas in the history of science (the *phylogeny* of the scientific knowledge) are similar to certain ideas and conceptions which students demonstrate during the course of learning (the *ontogeny* of the individual knowledge). Ideas such as "motion implies force," "motion implies impetus," "light fills space," and "the image moves from object to observer" are repeatedly shared by the history of science and by numerous students across nations, countries, and ages. Similar clear parallels may be found between students' understanding of vision and optical imagery (Galili and Hazan 2000b; Dedes 2005; De Hosson and Kaminski 2007). Therefore, even if this is not a case of recapitulation in the literal sense, there is a definite similarity between historical and individual progression from simpler erroneous to more complex ideas regarding light-vision conceptions. Despite the obvious differences from the past

resulting from metaphysical, sociological, and technological factors, the cognitive sameness of conceptual restructuring in science and education is suggestive (Nersessian 1989). Modern pedagogy may benefit from the history of science by using it to anticipate students' ideas and misconceptions during the course of learning (Wandersee 1986) and by learning from failures and errors in science (Kipnis 2010).[8] This interpretation legitimizes addressing Type-B knowledge in teaching using the history of optics.

The constructivist educational dictum of addressing students' conceptions in order to allow meaningful learning enhanced the remedial influence of addressing, analyzing, and discussing Type-B knowledge from the past. Consider, for instance, the conception developed by pre-Socratic scholars that an exact replica of an object comprised of atoms (*eidolon*) was continuously shed by the object in all directions (e.g., Russell 2002); this replica moved toward the observers and entered their eyes. Addressing and criticizing this kind of "holistic scheme" could assist those students who develop such ideas, causing a *cognitive resonance* leading to conceptual change and scientific understanding. Monk and Osborn (1997) and Duit et al. (2005) have recommended this pedagogy, and Galili and Hazan (2000b, 2004) have employed it in teaching optics.

3. Another view of the use of HPS materials in the teaching of optics makes use of *conceptual variation* in successful pedagogy. This approach was developed by Marton et al. (2004), who argued for a *space of learning* created by the variation of the target subject in teaching mathematics. It revived the scholastic method of analysis: to know a certain concept means to appreciate the different and possible alternatives. This method clearly calls for using Type-B historical knowledge to create the variations of the concept learned. For example, the history informs about the conceptions of optical image, such as holistic transfer (the Atomists), active vision (the Pythagoreans, Euclid, Ptolemy, Al-Kindi), point-to-point projection by light rays (Al-Haytham). All these conceptions are spontaneously produced by students (Galili and Hazan 2000b). All these conceptions can establish a space of learning from which students can be encouraged to discern the correct depiction of image creation as made by Kepler.
4. Finally, the fourth perspective, suggested by Tseitlin and Galili (2005), considers scientific knowledge to be a *culture of rules* (Lotman 2001). This perspective must be distinguished from the culture of science as social functioning (Latour 1987), from "science and culture" that placed scientific contents (physics, biology, astronomy) in the historical development of mathematics and natural philosophy (e.g., Fehl 1965), or from addressing ethnical aspects of knowledge in education (e.g., Aikenhead 1997; Aikenhead and Jegede 1999), and from considering the relationship of science and society (Bevilacqua et al. 2001) or art (e.g., Galili and Zinn 2007). Unlike all of these perspectives, Tseitlin and Galili consider the knowledge of physics *itself* as a culture.

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[8] The proponents of this approach quote "Those who forget the past are doomed to repeat it," attributed to George Santayana, and "Those who fail to *learn* from history are doomed to repeat it," Winston Churchill.

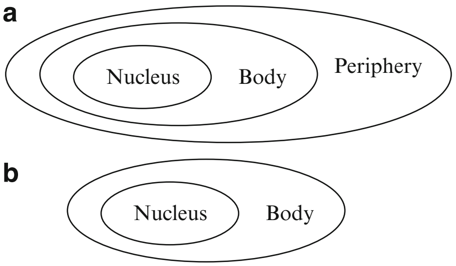

Fig. 4.3 (**a**) Schematic representation of the discipline-culture structure of a scientific theory. The elements of knowledge are located in three different areas. (**b**) Schematic representation of the discipline structure of a scientific theory

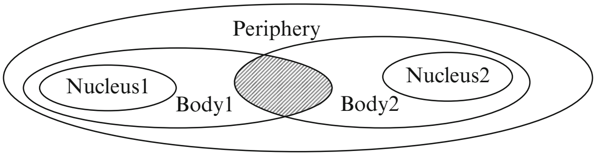

Fig. 4.4 Two fundamental theories in physics structured in DC form. Each nucleus is placed in the periphery of the other theory, thus representing the conceptual *incommensurability* of the nuclei, while the overlay of the bodies (*the shaded area*) represents their possible practical *commensurability*

Within this approach, fundamental physical theories possess a triadic structure termed as *discipline-culture* (DC): nucleus-body-periphery (Fig. 4.3a). This is instead of the regular disciplinary structure: nucleus-body (Fig. 4.3b).[9] The nucleus includes the fundamentals, the paradigmatic model, principles, and concepts, while the body is made up of various applications of the nucleus: solved problems, working models, explained phenomena and experiments, and developed apparatus. The periphery is the area incorporating the elements which contradict and challenge the nucleus, such as problems/phenomena which cannot be resolved/explained by a particular nucleus. Within this perspective, Type-A knowledge elements contribute to the nucleus and body, while the periphery accumulates Type-B knowledge elements contradicting the nucleus.

With respect to optical knowledge, there are four basic theories which emerged, developed, and were dominant in different historical periods: rays, classical particles, waves, and quantum particles (photons). The bodies of the theories define their areas of validity and partly overlap when different nuclei successfully explain the same phenomenon or experiment. Thus, if Fig. 4.4 represents the theories of waves (Fresnel) and classical particles (Newton), then the phenomena of reflection and refraction belong to the shaded area, strict geometrical shadow solely to the body of

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[9] Lakatos (1978) considered a similar structure when he described *scientific research programs*. However, the contents of all areas become different when one represents the knowledge of a fundamental theory as a culture.

particles, and diffraction solely to the body of waves. Photoelectric phenomenon would belong to the common periphery in this case. Teaching optics in a cultural way seeks to transform the naïve knowledge structured in scheme-facets (Fig. 4.2) into knowledge structured in DC form (Fig. 4.3a). This knowledge is defined as cultural content knowledge (CCK) and can be applied to teaching through the use of historical excurses (Galili 2012).

This suggested tripartite structure of knowledge cannot be linked in a simple way to the views of a certain scientist. Just as it is often impossible to identify an individual scientist with a single philosophical position (Galileo is a good example of such "inconsistency": empiricist in some cases and rationalist in others). The conceptual knowledge of a scientist may not allow full identification with one of these four theories of light. Descartes presents an illustrative example, as his view of light as a "successive propagation in space of a tendency to motion requiring no transport of matter" (Descartes 1637) is suggestive of a pressure wave in a medium of fine matter particles excluding the possibility of void in space. At the same time, he also actively used light rays to account for other phenomena (rainbow, vision, etc.) in a precise way. Thus, the identification of fundamental theories is valuable despite the specific, sometimes contradictory, positions of different individuals, as a way of determining the basis in which any system of views can be resolved as a vector to its components.

4.4.1 Example: Teaching the Concept of Optical Image Using a Historical Approach

Teaching the concept of optical image using history may take the form of an examination of several accounts of image created by means of light (Galili 2012). These accounts include the conceptions of "active vision" by the Pythagoreans, the Atomists' *eidola*, Plato's hybrid model, and Aristotle's transmission of tension through medium, all from the pre-theory period. Within the framework of the first optical theory – the theory of rays – established by Euclid, Al-Haytham in the eleventh century correctly explained optical image in a camera obscura and incorrectly explained the visual image created in a human eye. Kepler, in the seventeenth century, used flux of light rays and provided the explanation of vision which is currently taught in schools (Fig. 4.5).

The mentioned conceptions of visual image constitute a diachronic dialogue of scientific ideas. By teaching them to students, literacy in the history of science is improved (teaching approach 1 above), and the teacher is made alert to alternative conceptions spontaneously produced by students: holistic image (intromission), "active" vision (extramission), image projection point-by-point by single light rays, etc. (approach 2). A discussion of these conceptions of image formation may cause cognitive resonance, helping students to overcome their misconceptions (approach 2). The cluster of conceptions regarding optical image creates a specific space of learning in which the students may discern through comparison and contrast the scientific account of optical image (approach 3). Finally, contrasting and comparing selected historical accounts (Fig. 4.5) provides meaning for the light image conception to be learned – its cultural knowledge (approach 4). The inclusion of several

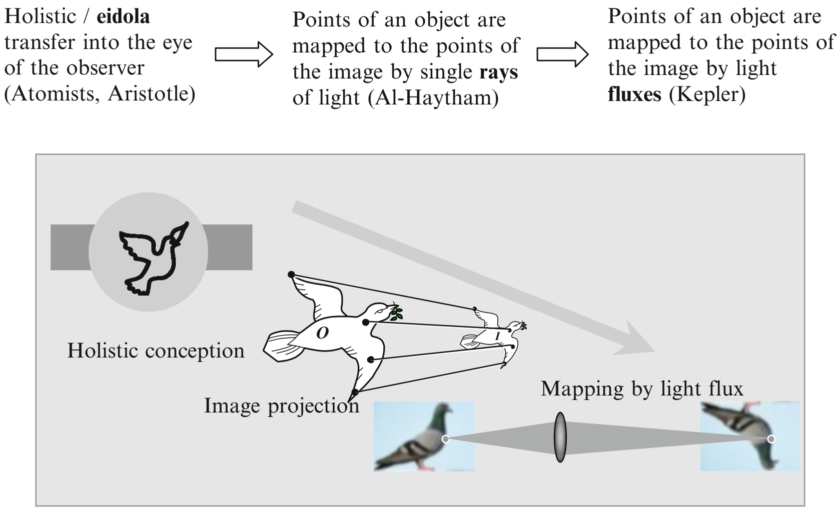

Fig. 4.5 Historical sequence of conceptions within the intromission understanding of optical images

alternatives of image understanding is meant to encourage students to appreciate the progress of theoretical fundamentals of any scientific issue and its continuous upgrading. This method of teaching surpasses instruction for "puzzle solvers" within the given paradigm (in the nucleus of a certain theory) (Kuhn 1977, p. 192) and suggests an awareness and appreciation of scientific progress.

4.5 Learning from Optics About the Nature of Science

Coping with the factors impeding understanding of optics creates an opportunity to learn about the nature of science and scientific knowledge. The latter includes *syntactic* knowledge, the ways in which the validity of knowledge is established, and knowledge *organization,* the structure of the subject matter (Schwab 1964, 1978). Both types of knowledge determine the *nature of science* (e.g., Kipnis 1998; McComas 2005, 2008). I will now review the possible impact of teaching optics in a culturally rich perspective involving the history of science with respect to several aspects of *scientific knowledge*.

4.5.1 The Role of Theory

Physics curricula often stress modeling as the major feature of physics, leaving the fundamental theories of physics in the shade. Theory is often mentioned as part of the opposition between theory and experiment, thus missing the centrality of the concept of theory and the fact that no experiment can be conceived without a theory.

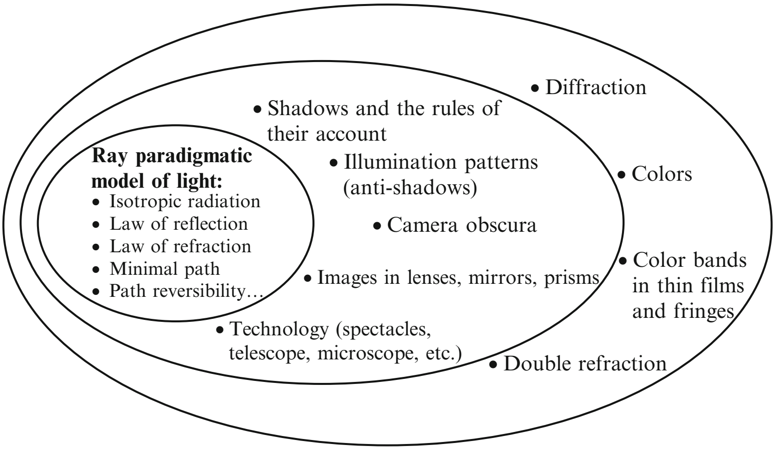

Fig. 4.6 Discipline-culture structure of the light theory of rays at the time of the scientific revolution of the seventeenth century. The contents of all three areas are illustrated

Experiments in science are normally *theory driven* and *theory laden* (e.g., Hanson 1958). Knowledge of optics demonstrates the organization of physics in terms of fundamental theories on a historical route from less to more advanced, thus creating a big picture of physics knowledge (Fig. 4.1).[10] Several accounts of light and vision reveal the polyphonic features of the scientific discourse, making scientific knowledge *cultural*.

Thus, at the beginning of science, scholars argued about intro- versus extramission conceptions of vision, the nature of light, and its speed, action, and behavior. Gradually, the first optical theory, the theory of rays, was developed through the efforts of many scholars from Euclid (third century B.C.) to Kepler (seventeenth century). They established Geometrical Optics.

The issues of color, light diffraction, and double refraction then emerged as challenging the theory of rays and those scholars who tried to save it, a situation which can be presented using a certain discipline-culture structure (Fig. 4.6). Newton's efforts to tackle the problem of light by "deducing" theory "from the phenomena" and avoiding the use of "hypothesis" (Newton 1729/1999, p. 943) were made within ray theory. He defined the light ray operationally in the first lines of his *Opticks* and proceeded from this concept:

> The least Light or part of Light, which may be stopp'd alone without the rest of the Light, or propagated alone, or do or suffer any thing alone, which the rest of the Light doth not or suffers not, I call a Ray of Light. (Newton 1704/1952, p. 1)

The strategy of staying with rays as the directly observed entity may lead people to consider Newton's *Opticks* to be a "neutral" investigation, especially the modern

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[10] One may locate the laws of reflection and refraction in the nucleus of the theory (as Newton did, see in the following) or in the body of knowledge, that is, being proved basing on the principles of light path being minimal/extremal and its being reversible (as Heron and Archimedes did with reflection in the Hellenistic physics and Fermat – in the seventeenth century, with refraction). Both ways are educationally valid given that they are supported in the course of teaching-learning.

reader who looks for Newton to take a side in the particle-wave controversy (Raftopoulos et al. 2005). It is indicative in this regard to compare Newton's accounts of light in the *Opticks* and the *Principia.* In the latter, he used the mechanistic theory of particles to *demonstrate* the law of (specular) reflection and Snell's law of refraction by considering particles interacting with matter (Newton 1727/1999, pp. 623–625), while in the former he *postulated* the same laws, thus placing them in the nucleus of the theory of rays (Newton 1704/1952, p. 5).

In order to explain color dispersion, Newton introduced the idea of light rays varying in refrangibility – color rays. Applying the classical method of *resolution* and *composition*, used by Aristotle, medieval scholars, and Galileo (Losee 2001, p. 28), Newton decomposed sunlight into the color spectrum and then, to remove speculations about the "creative" role of the prism, resynthesized white light by combining colored lights (Boyer 1987; Gaukroger 1995, p. 265).

Newton proceeded to use rays to explain the pattern of color rings as due to a thin layer of air of varying thickness between lens and plate (Newton's rings). Today, this is clearly an interference phenomenon, but it was not so for Newton, who explained it within the ray theory and without interference by ascribing to each ray a periodicity of "fits," predispositions to the reflection of the light ray from or penetration into the transparent medium (Tyndall 1877; Westfall 1989; Kipnis 1991; Shapiro 1993).[11]

Newton then turned to the diffraction of light and meticulously reproduced and refined the experiments of Grimaldi (1665). He rejected the suggested by Grimaldi splitting light into regular and extraordinary components in order to explain the light fringes next to the edge of geometrical shadows (Gliozzi 1965, pp. 121–122; Taylor 1941, p. 516) and replaced Grimaldi's *diffraction* with a *inflection* of rays. Yet, he failed to produce a theoretical account of light inflection. After a detailed description of the phenomena in numerous settings, he abruptly stopped because of "being interrupted" – a dramatic turn in a scientific treatise:

> When I made the foregoing Observations, I design'd to repeat most of them with more care and exactness, and to make some new ones for determining the manner how the Rays of Light are bent in their passage by Bodies, for making the Fringes of Colours with the dark lines between them. But I was then interrupted, and cannot now think of taking these things into farther Consideration. (Newton 1704/1952, pp. 338–339)

Some years before, Huygens, in his *Treatise on Light*, had tried to explain double refraction within his wave theory. He succeeded in using his inventive geometrical account of anisotropic expansion of light in a crystal to describe light beam splitting in a single crystal of calcite (Iceland crystal), but he failed to explain the behavior of the light beam passing through two crystals placed one after another. The beams amazingly change their refraction in the second crystal. Somewhat similar to Newton he quit:

> Before finishing the treatise on this Crystal, I will add one more marvelous phenomenon which I discovered after having written all the foregoing. For though I have not been able till now to find its cause, I do not for that reason wish to desist from describing it,

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[11] Newton's numerical results on ray periodicity were of unprecedented accuracy for his time: for yellow-orange ray it was 1/89,000 in. (Newton 1704/1952, p. 285), well conforming to the half wavelength known today.

> in order to give opportunity to others to investigate it. It seems that it will be necessary to make still further suppositions besides those which I have made …. (Huygens 1690/1912, p. 92)

Newton, after the main text of the *Opticks*, added *Queries*, where he described his considerations and hypotheses regarding the nature of light. Exactly as Huygens before him, Newton addressed the future researchers:

> And since I have not finish'd this part of my Design, I shall conclude with proposing only some Queries, in order to a farther search to be made by others. (Newton 1704/1952, pp. 339–406)

Only there, in the *Queries*, did Newton allow himself to speculate: "Are not rays of light small particles emitted by shining substances …?" and argued for the advantages of the *corpuscular* nature of light over the *wave* theory suggested by Huygens. There, addressing double refraction (birefringence), Newton stretched the ray theory even further and introduced *sides* to the light rays – a primitive version of the polarization of light (Mach 1913/1926, p. 189). In this way, he suggested a qualitative explanation of light passing through two consecutive crystals, the phenomenon which had puzzled Huygens (Newton 1704/1952, Query 26, pp. 358–361).[12] Newton finally quit, but not before he expressed his preference for the *particle* nature of light.

Thus, in the contest between two seventeenth-century theories, particles and waves each presented its successes in accounting for light (the body of the theory) and admitted its failures (the periphery). Newton's conjecture of light particles was definitely not treated as a theory Newton would prefer (as he did in mechanics[13]), but even so, it was preferred to its rival – Huygens' wave theory. In the end, though, neither scholar managed to produce an overall theory of light. Hakfoort states that:

> From about 1700 the *Traitĕ* [*Treatise on Light*] was almost completely ignored even in research reports from within the medium tradition. (Hakfoort 1995, p. 53)

Newton's conception of light particles remained dominant throughout the eighteenth century (Britannica Encyclopaedia 1770/1979), until Thomas Young and Augustin Jean Fresnel accounted for several new experiments and succeeded in demonstrating the clear superiority of the modified wave theory by introducing the principle of interference (Lipson 1968; Kipnis 1991). The nineteenth century witnessed the triumph of Fresnel's wave theory, which seemed to be unlimitedly true beyond any doubt, but not for a long time. In the twentieth century, new problems emerged to challenge the wave theory. To account for them Plank in 1900 and Einstein in 1905 produced heuristic models of light quanta. Placed in the periphery of the wave theory (Fig. 4.7), these constructs led to the new theory of light – the quantum theory, or the theory of photons.

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[12] The quantitative account of the polarization of light was provided much later by Malus in the nineteenth century (Malus' law), who introduced and described the polarization of light particles instead of Newton's *sides* of light rays.

[13] The list of Newton's successes should also include the dynamic account of light behavior in the *Principia* and Newton's polemics there with Descartes' paradigm of plenum.

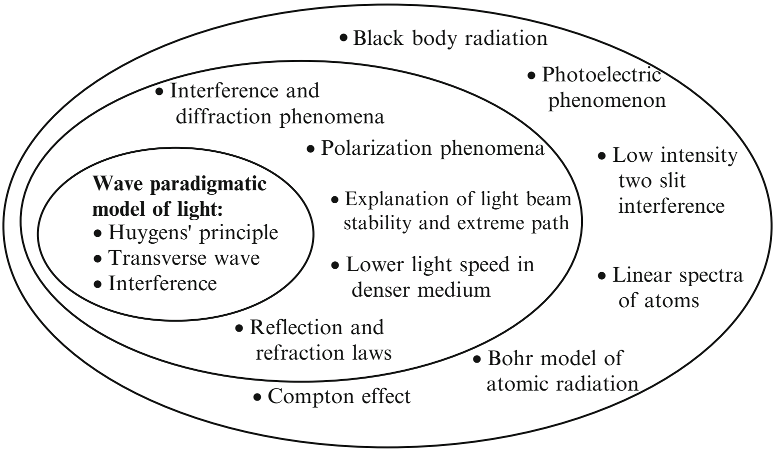

Fig. 4.7 Discipline-culture structure of the light theory of waves prior to the scientific revolution of the twentieth century

At each moment of history, the dominant theory of light can be represented as possessing the discipline-culture structure exemplified in Figs. 4.6 and 4.7. This presentation visualizes teaching about the transition between the successive theories of light and the competition between them. The dramatic contest of theories of light reveals the big picture of optical knowledge organized in terms of theories. Such a picture could be presented to the students in the form of summary ("vista point") lectures following a regular course (Levrini et al. 2014) or as a part of class instruction in a specially designed curriculum (Galili and Hazan 2000b).

4.5.2 The Role of Experiment

Teaching optics historically can be used to illustrate the role of experiment in physics knowledge. This topic is often addressed in the context of the opposition between theory and experiment.[14] A class discussion may begin from an examination of the famous image by Raphael Sanzio (Fig. 4.8) manifesting the symbiosis of rationalist and empiricist approaches as the essence of science.

For instance, the two optical theories of the seventeenth century differed with regard to the speed of light in transparent media. Newton implied that the speed of light in a dense transparent medium (water) would be higher than in a rare one (air); the wave theory of Huygens stated the opposite (e.g., Sabra 1981, pp. 217, 302). Both theories produced Snell's law of refraction and equated the refraction index to v_1/v_2 or, alternatively, to v_2/v_1.

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[14] In the cultural approach, experiment may be affiliated to either body or periphery area within the triadic structure of theory knowledge.

Fig. 4.8 Plato and Aristotle in Raphael Sanzio's fresco *The School of Athens* (c. 1511). The gesturing of the two philosophers is commonly interpreted as emblematic of the epistemological dispute between rationalism (theory first) and empiricism (experience first) (See, for example, Galili (2013))

The opposing conclusions regarding the speed of light in different media could not be resolved using theoretical tools. New experiments were required. Augustin Fresnel and François Arago, as early as 1816, demonstrated experimentally that light traveled slower in glass (mica) than in air (Kipnis 1991, p. 178). Born (1962, p. 97) has emphasized the experimental confirmation of this result by Leon Foucault in 1850 (Foucault 1854). In both cases, however, the voice of experiment was decisive; theories could not manage without experiment. Given the central role of theory,[15] the students may learn to appreciate the fundamental complementarity between theoretical and experimental considerations as the essential feature of scientific account of any subject. Specific cases where experiment surpasses theory (Brush 1974) may further illustrate the reciprocity of the theory-experiment relationship. All in all, the idea that the validity of a theory in physics demands the firm basis of pertinent experiments is comprehensively represented.

The victory of the theory of relativity may be used to further refine the relationship between theory and experiment, which is often presented as drawing on a single experiment by Michelson and Morley: light interference in the moving interferometer. A cultural historical presentation reveals that rival theories (aether drag, emission theory, length contraction) provided alternative explanations for the same experiment. The victory of the special theory of relativity emerged from a series of different experiments where only Einstein's theory was able to account for all the results (Panofsky and Phillips 1962, p. 240). This way one physical theory replaces another.

The same context is appropriate for a discussion of the historically popular idea of the "critical experiment" (*experimentum crucis*). The history of light contains a series of such experiments, but a closer look often displays a more complex picture.

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[15] See Sect. 4.5.1.

Texts often mention Newton's prism experiment as proof that light is composed of colored rays (e.g., Wolf 1968, pp. 264–271; Boyer 1987, pp. 200–268), Poisson's spot experiment is seen as proof of the wave theory of light (e.g., Kipnis 1991, pp. 220–222), and Foucault's experiment on the speed of light in water is also taken as proof of the wave theory. Although the need for concise teaching is understandable, the teacher may mention a mature understanding of "critical experiments" as indicating and suggesting, but never addressing all the possibilities in clarifying the truth about nature. Duhem (1982, pp. 188–190) made just this point when he addressed the nature of light and wrote: "The truth of a physical theory is not decided by heads or tails." Popper (1965, pp. 54–55) followed him and stated that the power of experimental evidence may serve as a strong argument in theory refutation, rather than proof of its being "true." The physics teacher should moderate the strong convincing appeal of "critical experiments" within the cultural teaching of optics. Yes, sunlight includes all colors, but is it composed of *rays*? Yes, light possesses a wave nature, but can one qualitatively explain the Poisson spot by a sort of Newtonian inflection of light rays? Similarly, can Foucault's results on the speed of light in water be explained by Fresnel's drag coefficient of the aether? An experiment may serve as a great step forward, but science always proceeds by seeking a variety of evidence for the same theory.

Finally, one of the most impressive illustrations of the decisive role of a real experiment may be the famous EPR experiment on a pair of entangled photons. Designed as a thought experiment by Einstein in 1935 with particles (later translated by Bohm to the experiment with photons), it was meant to demonstrate the "incomplete" nature of quantum mechanics. The experiment drew on a theoretical assumption which was considered to be unquestionably true – the principle of the locality of physical events (e.g., Cushing 1998, p. 325). For years this *thought* experiment remained an open problem kept in the periphery of the quantum theory in order to question its major paradigm. The *real* experiment carried out by Aspect in 1981 with pairs of entangled photons radiating in opposite directions provided the verdict: quantum physics is correct, Einstein was wrong. Microscopic objects are subject to the principle of nonlocality (e.g., Cushing 1994, pp. 14–16; Penrose 1997, pp. 64–66). From the periphery of quantum theory, the EPR thought experiment migrated to its body as a real experiment, but not before the principle of nonlocality was added to the nucleus of quantum theory. The historical teaching of light, thus, clarifies the complex and reciprocal relationship between theory and experiment. This complementarity implies an essential entanglement which can be expressed in the terms of the Bohr principle (e.g., Migdal 1990).

4.5.3 Cumulative Nature of Scientific Knowledge

Among the advantages of the historical perspective is its ability to illustrate the cumulative character of scientific knowledge. Kuhn's (1962/1970) thesis about periods with conceptually incommensurable paradigms (nuclei of the dominating theories) is often interpreted excessively as a renouncement of the idea of cumulative knowledge in science, despite Kuhn's own clarification in his postscript of 1970 (ibid, pp. 205–207). A historical view of optics allows the refinement of this subject while displaying the continuous progress of knowledge accumulation and use. At each stage, scientific research is inherently related to previously obtained results. Even though there are different theoretical frameworks in each historical period, similar or even identical questions were tackled, drawing on information from previous studies either positively or negatively.

Thus, a teacher may introduce the old problem from Aristotle's *Problems* (Aristotle 1952, pp. 334–335): in the camera obscura a small opening leads to a circular image of the sun, while a large opening produces an illuminated area in the shape of the opening (Lindberg 1968). More than 1,300 years later, Al-Haytham resolved this mystery when he applied a concept introduced by Al-Kindi about 200 years earlier: light expands from *each* point of a light source in *all* directions. Al-Haytham's account for the image in the camera obscura was adopted by della Porta a few hundred years later; in the sixteenth century he suggested that the human eye is similar to the camera obscura but with a lens in the hole. Kepler, in the seventeenth century, resolved the enigma of vision in dialogue with the scholars of the past. He used his knowledge of Euclid, Al-Haytham, and others to resolve the problem they failed to solve. The power of knowledge accumulation is that which Bernard of Chartres (twelfth century) epitomized in his famous pronouncement so relevant to scientific knowledge and science education:

> We are like dwarfs standing on the shoulders of the giants, so that we can see more things than them, and see farther, not because our vision is sharper or our stature higher, but because we can raise ourselves up thanks to their giant stature. (Crombie 1959, p. 27)

In another example, an optics instructor may follow up the principle of the propagation of light in space starting from the statement of *minimal* path length in specular reflection by Heron the Hellenist. Fermat later refined the same principle for the *extreme* path in terms of the time required by light. In 1871 Lord Rayleigh used the Fresnel zone plate to experimentally demonstrate the Huygens-Fresnel principle of the propagation of light (Mach 1913/1926, p. 287; Hecht 1998, p. 487). He demonstrated that light moves not only in straight lines between any two points but in all other ways between them. The old argument of Newton (1729/1999, pp. 762–765) against the wave nature of light was thus removed. The idea of multiple paths of light led Feynman (1948, 1985) to the most fundamental principle of quantum electrodynamics – multiple intermediate events or paths, in general sense, between any two states. Over the centuries, scholars working within different paradigms constructed physics knowledge about the expansion of light.

In a sense, scientists have maintained conceptual discourse, diachronic and synchronic, on research questions and drawn on previously attained understandings. As Collingwood stated in his *The Idea of History*:

> The two phases [of science] are related not merely by way of succession, but by way of continuity, and continuity of a peculiar kind. If Einstein makes an advance on Newton, he does it by knowing Newton's thought and retaining it within his own, …. He might have done this, no doubt, without having read Newton in the original for himself; but not without

> having received Newton's doctrine from someone. … It is only in so far as Einstein knows that theory, as a fact in the history of science, that he can make an advance upon it. Newton thus lives in Einstein in the way in which any past experience lives in the mind of the historian, … re-enacted here and now together with a development of itself that is partly constructive or positive and partly critical or negative. (Collingwood 1956, p. 127)

An awareness of this aspect of the scientific knowledge promotes cultural content knowledge.

4.5.4 Objective Nature of Scientific Knowledge

Traditionally, the objectiveness of an account of nature is understood by scientists to mean the independence of this knowledge from will, mood, desires, etc: "the way whether and how the dropped object falls is independent of our attitude to that"; scientific accounts of phenomena should be objective in this sense, and thus scientists often state that physics is *objective* (e.g., Weinberg 2001). *Only* such objective knowledge can be the subject of critical discourse maintained by science, indicating its "health" (Popper 1981; Holton 1985). However, as mentioned by Einstein (1987), the particular system of concepts scientists use in their account of nature is the result of their free decision further tested by experiment. It is not surprising, therefore, that some researchers have highlighted the subjective features of scientific knowledge, its dependence on imagination, beliefs, worldviews, social constraints, etc. (e.g., McComas 1998, 2005). Their emphasis on the interaction between the "instrument" (the scientists) and the object (the nature) has been illustrated by Kierkegaard:

> … The speculative [philosophers] in our time are stupidly objective. They completely forget that the thinker himself is simultaneously the musical instrument, the flute, on which he plays. (Kierkegaard 1952, quoted in Migdal 1985)

In contrast, many philosophers and historians of science believe that "the metaphysical tenets of individual scientists, though often quite strong, are generally so varied, so vague, and so technically inept that in a sense they cancel out, made ineffectual by the lack of a basis for general acceptance and agreement of such tenets" (Holton 1985). That is, variation among individuals is essential in the search for objectiveness. The history of science enhances this claim.

Within the historical teaching of optics, the issue of objectivity may be illustrated, discussed, and provided with operational meaning. Consider the principle regulating light path. Heron of Alexandria in his *Catoptrics* demonstrated the rule of the specular reflection of light: the light path presents the shortest trajectory between any two points, including mirror reflection (Cohen and Drabkin 1966, p. 263). This rule is an example of objective knowledge. However, the interpretation of this result as nature seeks the most "economical" way to go, or that nature does nothing in vain (*natura frustra nihil agit*), is a subjective, metaphysical one. Furthermore, using the method of *Maxima and Minima,* Fermat in the seventeenth century advocated the *extreme* temporal rather than spatial path of light (Ross 2008), an objective truth. However, he also claimed that his finding expressed a "natural intention," a subjective view. Measurement confirmed the law of refraction as the sine ratio of the angles of incidence and refraction, objective knowledge. Descartes believed that this empirical law of refraction was not sufficient because it did not *explain* the phenomenon. He suggested an ad hoc mechanism of light refraction (Descartes 1637/1965, p. 79), claiming an analogy between light and the motion of a ball being hit downward by a tennis racket at a water surface (Ross 2008, p. v). This analogy was used to explain the increased vigor of the ball in water. Given that Descartes did not ascribe velocity to light, the artificial and subjective nature of this analogy is obvious. Mach called it "unintelligible and unscientific" (Sabra 1981, p. 104), but the approach of Fermat, Descartes' opponent, was unsatisfactory as well: how and why could light possibly "decide" on the extreme path?

Only in the nineteenth century were the subjective speculations regarding light propagation removed, following the introduction of wave interference by Fresnel as a tool to apply Huygens' principle. The experiment by Raleigh who covered odd (or even) Fresnel zones on the screen placed on the light way demonstrated that light did not "decide" which way to go from one point to another but went in all ways between these two points. The interference of all the beams produces the familiar phenomena of light reflection and refraction. Thus, the *subjective* part associated with the Fermat principle was dismissed, and the *objective* one remained. Feynman (1948, 1985) further developed this new understanding to include particles with mass. An introductory optics course can, and in a way should, display a qualitative account of the full story.

The objectivity of physics knowledge was framed within the idea of the "third world"[16]: the virtual intellectual space incorporating physical theories (Popper 1978, 1981). Disconnected from individuals, it contains objective knowledge of the world. Holton (1985) introduced science-1 and science-2 for the same purpose – to distinguish between the objective core and subjective elements of physical theories. The four theories of light illustrate an area of optics knowledge in the third world. Though very different in validity, they share the property of objectivity, remaining human, that is, a subject for refinement and falsification.

4.5.5 The Role of Mathematics

Mathematics provides one of the central features of physics knowledge. Its role in physics is important, complex, and many faceted. The history of optics is eloquent in this regard. Euclid, Archimedes, and Ptolemy were the first to introduce mathematics into the optics of Hellenistic science, addressing the features of light and vision (e.g., Smith 1982; Russo 2004). In this way they rebelled against the previously dominant perspective of the Hellenic philosophers who argued for a qualitative conceptual account of nature as the major agenda of physics. Euclid introduced

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[16] To be distinguished from the real world (the first one) and the personal world (the second one).

the central mathematical tool of optics – rays of light and vision – and developed the method of *perspective* (two-dimensional representations of three-dimensional reality). In his hands, optical theory became a brunch of geometry. Great mathematical skill, however, was not enough to allow him to explain the nature of light and vision and prevent fundamental confusion. Indeed, Euclid, Ptolemy, Al-Kindi, and many others mastered perspective but held and skillfully argued for the faulty ideas of active vision ("eyes radiate vision rays …," scan the reality) (Lindberg 1976). In physics class, this combination of advanced and erroneous views by the same scholars may contribute to understanding features of the relationship between mathematics and physics.

Another example of this kind is the history of the sine law of refraction. Ptolemy was the first to tackle the problem (Ptolemy 1940; Smith 1982; Mihas 2008). His data did not fit the constant proportionality between the angles of incidence and refraction of visual rays. Ptolemy tried to "adjust" their behavior to a quadratic dependence (Russo 2004, p. 64). Light rays behaved in the same way, as they were postulated to follow the same path as vision but in the opposite direction. However, the true ratio known as the sine law was not obtained by Ptolemy. Smith (1982) has explained this failure by the fact that Ptolemy, like Heron, only used spatial (geometrical) considerations of the vision-light path, while the key to the true account of refraction, the explanation, was to treat the problem using temporal (kinetic, physical) considerations, as Descartes and others did much later (e.g., Sabra 1981, pp. 105–116). Thus, obtaining the correct mathematical account in Hellenistic physics was impeded by an inappropriate physical approach: geometry and numbers were not enough.

For centuries scientists kept trying to find the mathematical form of the refraction law. Even in the seventeenth century, a skillful mathematician like Kepler, who had famously proved himself by his demonstration of the elliptical orbits of planets and who wrote prolifically on optics and vision, failed to reveal the refraction law, perhaps because he trusted the not sufficiently accurate tables of Vitello (thirteenth century) (Herzberger 1966). Kepler continued to use the linear dependence of angles ratio as a good approximation of refraction at small angles.[17] Eventually, several scholars worked out the correct law: Ibn Sahl (c. 984), Harriot (c. 1602), Snell (c. 1621), and Descartes (c. 1637) (Sabra 1981; Rashed 2002, p. 313; Kwan et al. 2002). As mentioned, the first explicit explanations of this law involved physical considerations regarding the speed of light. Ironically, it was Descartes who first elaborated the demonstration of the law, despite his own denial of the finite speed of light.

History tells us that the mathematical form itself and even its deduction from Fermat's principle of extreme time of light trajectory (the "easiest course" and the principle of economy) did not suffice for physicists. Scientists wanted to know the *mechanism* which caused this particular form of the refraction, the mechanism that underpins the rather unusual mathematical form of the sine law. Descartes' artificial

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[17] This simplified law of refraction can be used in teaching optical phenomena presented qualitatively (Galili and Goldberg 1996).

analogy of the ball entering the water was not at all persuasive.[18] In contrast, Huygens and Newton were more convincing. Both scholars reproduced Snell's law theoretically, even though they based themselves on the contrasting models of waves and particles. Drawing on the particle model, Newton supported Descartes' conjecture; the velocity of light in a denser medium increases, perhaps due to the gravitational attraction of the medium. Huygens, however, deduced the same law from his principle of secondary waves and inferred the opposite – the lower velocity of light in a denser medium (Sabra 1981, pp. 300–302). Mathematics falsified all the other options but could not help to choose between the two remaining theories. This choice was made by physicists in the nineteenth century.[19]

In the contest of theories of light, Huygens surpassed Newton in the mathematical accuracy of his account of double refraction in a single crystal of Island spar, but, as already mentioned, he failed to explain the behavior of light in two successive crystals. Newton, addressing the same phenomenon, correctly suggested the transverse polarization of light by his assumption of light ray *sides* but did not provide a mathematical account of double refraction. The framework of the wave optics of Fresnel in the nineteenth century was necessary for this account. In retrospect, in the seventeenth century researchers lacked the essential mathematical tools required to account for the transverse running wave: two-variable functions to depict a running wave, equations in partial derivatives for a wave equation, and calculus of the kind Fresnel applied to the principle of interference. Newton, who performed a revolution in mathematics by inventing calculus to account for gravitation, did not instigate another mathematical upheaval required to account for optics.

The examples of the history of optics mentioned here clearly demonstrate that mathematics and physics are fundamentally entwined. Like theory and experiment, the relationship between mathematics and physics can be expressed in terms of complementarity in the sense introduced by Bohr (e.g., Migdal 1990, p. 16). Einstein expressed a very close idea, saying "As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality." In summary, Einstein's addressing the relationship between physics and philosophy may be paraphrased to conclude that mathematics without physics is blind (i.e., unable to provide qualitative understanding and causal meaning), while physics without mathematics is empty (i.e., destined to produce unresolved speculations which might be conceptually valid but untestable).

4.5.6 Commonsense Complexity

Another important feature of scientific knowledge to reveal by teaching optics in a cultural historical perspective is its relationship with common sense. The history of optics is eloquent in this respect as well. Thus, for years, many scholars could not

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[18] See Sect. 4.5.4.

[19] See Sect. 4.5.2.

accept the idea of the "upside-down" image created on the retina of the human eye, despite the fact that since antiquity it had been known that the retina, and no other part of the eye, is connected to the brain. The inverted image observed in the camera obscura and on the screen placed behind a convex lens did not seem to be relevant, apparently contradicting common sense. This "obviousness" misled great minds. Al-Haytham erroneously placed the "correct," right-side-up image on the surface of the eye lens. Later, Leonardo da Vinci painstakingly searched for two successive inversions which would provide a right-side-up image. Only Kepler, in the seventeenth century, removed the enigma: common sense is lying – the image in the eye is inverted and is dealt with as such by the mind – another stage in the process of vision (Lindberg 1976).

Another example deals with the nature of light. Since people do not usually feel light entering the eye, common sense conceives of light not as a moving agent but rather as a state or medium; light "fills" and "stays" in space. Light as a static entity fits the biblical description of the creation of the world and the commonsense conceptions of students. The historical teaching of optics may address this topic in relation to the difference between the visual perception of light and its objective existence – an epistemological issue (Gregory 1979; Linn et al. 2003). This interesting topic can be related to the historical split in the concept of light: lux seems to be close to our concept of illumination, while lumen seems to represent light as physical entity (Steneck 1976; Galili and Hazan 2004). Lux and lumen are Latin terms introduced in the translation of the Bible to Latin (the original text in Hebrew has no such split, though the split in the meaning of light is discussed in religious sources).

Discussing the existing versus perceived dichotomy in physics may lead students to a critique of naïve common sense and an understanding of its difference from scientific knowledge (Cromer 1993; Wolpert 1994) and yet its necessity in doing science (Conant 1961; Bronowski 1967). Koyré (1943) has stated that the role of the founders of modern science was "to replace a pretty natural approach, that of common sense, by another, which is not natural at all." Einstein wisely moderated this extreme claim by saying that science continuously refines and corrects common sense. Science "upgrades" common sense and transmits the benefits of the changes to all through public education.

4.5.7 Teaching Modern Physics

There is an interesting pedagogical phenomenon: unlike the teaching of classical physics, which often ignores the history of science, the teaching of introductory modern physics is normally historical and reproduces step by step the transition from classical physical theories to modern ones. A historical narrative mitigates the overwhelming conceptual novelty of relativistic or quantum physics and the significantly more complex mathematics which they employ. The teaching of modern physics usually starts by addressing the problems of the light theory of waves from the periphery of that theory (Fig. 4.7). The events of the beginning of the twentieth century gradually introduce the student to modern theoretical and epistemological perspectives on the objective reality with regard to light. In this context, the discoveries become interwoven with the construction of the new theory.[20]

Fizeau's experiment on the propagation of light in moving water (Fizeau 1851) can illustrate the particular teaching potential of the culturally-framed teaching of modern physics already-mentioned[21] with respect to the Michelson-Morley and EPR experiments. This example well illustrates the principle of the correspondence of physical theories. Initially, Fresnel's model of the partial drag of the aether, the "drag coefficient" (Fresnel 1818), saved the appearance of Fizeau's experiment by providing an explanation of the experimental results. However, the theory of special relativity, based on fundamentally different ideas, reproduced the drag coefficient as the first approximation of the more accurate relativistic account (e.g., French 1968, pp. 46–49). It was thus shown that the new theory was able to explain the previous accounts and in a more accurate way.

Another item of optical history illustrating the quantum nature of light is the two-slit experiment in which a very low intensity light beam creates an illumination pattern of interference as emerging from the accumulation of numerous separate spots – the experiment by Geoffrey Ingram Taylor (1909). When there is a much larger number of photons, and after a considerable amount of time, the regular interference pattern of two-slit experiments emerges, reproducing the classical result of Young (1804) and Fresnel (1866). Taylor's experiment demonstrates the intimate relationship between two theories of light – quantum and classical electromagnetic. When students are presented with the discipline-culture structure, the two theories possess distinguished nuclei and partially overlaid bodies of knowledge (Fig. 4.4).

4.6 Conclusion

Teaching optics using HPS is possible and beneficial. This pedagogy clarifies the disciplinary knowledge of light and vision as well as the nature of scientific knowledge. The validity of the *cultural content knowledge* established in this way in the student goes beyond the mere correction of misconceptions. A curriculum enriched by HPS addresses the creation of knowledge which took place in both diachronic and synchronic scientific discourse. Both essentially involve elements of incorrect in disciplinary sense knowledge which is inherently connected to and elucidates the meaning of correct knowledge. This approach takes advantage of the similarity,

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[20] Educators may use an artistic metaphor to represent the transition from the epistemological credo of classical physics to that of the modern theories. The relief on the Nobel Prize medal for physics can be seen as representing the epistemology of classical physics, while a sketch depicting the myth of *Pygmalion and Galatea* may do the same for modern physics (Levrini et al. 2014; Galili 2013).

[21] See Sect. 4.5.2.

though not identity, between students' ideas regarding light and vision and those developed in the course of the history of science, causing cognitive resonance in the students.

The beneficial impact of dealing with the historical knowledge of optics expands on understanding of the nature of science and the fundamental features of scientific knowledge. This impact deserves more investigation in the perspective of considering physics knowledge as a culture. Introducing a discipline-culture structured curriculum allows understanding of the role of HPS in optics knowledge representation, and the dynamic relationship between the four basic optical theories otherwise often remains disconnected for being taught in different courses. The introduced integrated picture emphasizes the image of science as theory-based knowledge (e.g., Bunge 1973) and removes the oversimplified perception of incommensurable theories of light, thus upgrading the meaning of their relationship in a big picture.

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Chapter 5
Teaching and Learning Electricity: The Relations Between Macroscopic Level Observations and Microscopic Level Theories

Jenaro Guisasola

One of the areas of research in physics education boasting the highest number of works over the last three decades is electricity. Numerous studies on the teaching and learning of electricity have been conducted (Duit 2009). Two reasons for this high number of studies in the area of electricity will be discussed next.

First, electrical phenomena and its properties are an important part of physics instruction at many different levels. Students learn about the idea of charge and electrical circuits in elementary school and gradually integrate more complex ideas to interpret electrical phenomena. Studying the models needed to interpret electromagnetic phenomena is a productive area: it provides a solid background to understand issues that range from the electromagnetic nature of matter to the foundation of contemporary technology. The structure of the electromagnetic nature of matter is both beautiful and useful.

Furthermore, electromagnetic theories provide a good context for teaching scientific reasoning skills such as model-building and model-drawing relations between macroscopic level description phenomena and microscopic level theories. As research shows, many times learners need to have the ability to reason holistically. Psillos (1998) shows the necessity of global reasoning for analysing the components of the electric circuit. Viennot (2001) explains that overcoming the "causal reasoning" and/or the "reasoning based on the formula" is a necessary condition for understanding electric circuits and other areas of electricity.

Second, electricity is an area of physics that students find significantly more difficult to understand than mechanics. Comprehension levels for electricity concepts are highly idiosyncratic. Moreover, literature shows confusion between electricity concepts and the terminology used in everyday life (e.g. electricity energy, voltage, electric power). This comes as no surprise due to the complexity of the concepts involved, but it is more disconcerting that this lack of understanding remains almost unchanged by teaching (McDermott and Shaffer 1992; Wandersee et al. 1994).

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Research carried out on new proposals to improve the situation offers unequal results (Mulhall et al. 2001). Some studies present specific progress whilst others do not. As a consequence two main problems can be identified: (1) students' prior knowledge interacts strongly with the teaching strategies used, producing a wide variety of learning achievements (Saglam and Millar 2005), and (2) teaching strategies have to combine the macroscopic level electric phenomena and the microscopic level theory (Chabay and Sherwood 2006; Young and Freedman 2008).

5.1 Issues Emerging from Physics Education Research

The main line of research on teaching and learning electricity over the last few decades has focused on studying students' alternative conceptions (Driver et al. 1994, Wandersee et al. 1994). In the case of DC circuits and electrostatics, research suggests a consensus about the main learning difficulties.

Current thinking suggests that prior knowledge and students' conceptions interfere and affect their learning in new contexts (Ausubel 1978; Duit and Treagust 1998). These assumptions set up the students' scientific skills, and as Etkina and colleagues (2006) state, "… these (scientific skills) are not automatic skills, but are instead processes that students need to use reflectively and critically" (Vosniadou 2002, p. 1). Conclusions without evidence or employing a single strategy, which generally involves specific and direct application of a "recipe", are common occurrences (Guisasola et al. 2008; Viennot 2001).

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Alternative ideas about electromagnetic phenomena can arise from the academic context, as it requires elaborate knowledge far removed from daily life. As the physics contents within a teaching programme and the textbooks are part of the academic context, it is particularly necessary to carry out research on them and their effect on learning.

In order to present the main learning difficulties and alternative ideas detected by the research, they are grouped into different conceptual aspects from electricity. It does not follow a historical development of the research findings but criteria relating to the conceptual physics framework and its relation to the electricity curriculum. However, different research projects have shown that alternative conceptions are not random ideas, but they have some internal cohesion, structured in "alternative conceptual framework" (Oliva 1999; Watts and Taber 1996). The findings presented here in each subsection most often refer to related aspects, so their view of the whole concept should not be lost.

5.1.1 Students' Difficulties in Learning Electrostatic Phenomena and Electric Fields

University physics textbooks present electrostatics before DC circuits, different from secondary courses (ages 12–16) that start with DC circuits without explicitly analysing the electrostatic electrification phenomena or explaining a model for the electrical nature of matter (Stocklmayer and Treagust 1994).

Until the present, few studies have addressed learning difficulties in electrostatics. Problems exist in the failure to learn about the scientific models that are used to interpret basic electrostatic phenomena such as interactions between point charges, phenomena involving friction charging or electrical induction charging.

Galili (1995) shows that in Israel students aged 16–18 and future secondary teachers apply Newton's third law superficially (a difficulty observed in work on alternative conceptions in the field of mechanics) and have serious difficulties when analysing the polarisation of a metal under electrical interactions, difficulties that derive from alternative conceptions of mechanics.

According to Furio and colleagues (2004), Spanish students aged 17–18 demonstrate different alternative conceptions when interpreting electrification phenomena due to friction or induction. A majority of students consider electricity as a fluid composed of particles that can be transmitted through conductors. For electrical interaction to take place, the fluid must go from one body to another. Students in this category are not able to scientifically explain phenomena that involve remote actions, such as electrical induction and polarisation of matter. Only a minority of students use the Newtonian model of action at a distance to explain the phenomenon of remote electrification and, consequently, to give a scientific explanation of induction and polarisation phenomena. In addition, in a study with Korean middle school and college students on their ideas regarding electrostatic induction, Park and colleagues (2001) found that many students show a lack of understanding about dielectric polarisation, even though this concept is basic to everyday experiences, such as the attraction of a piece of paper through the rubbing of a comb. Moreover, some middle school students misunderstood the role of an electroscope and were not sure about which material was a conductor or a non-conductor.

In the study of electrostatics, electric field and electric potential are two important concepts. Research into students' difficulties shows that the vast majority do not have a scientific grasp and make incorrect applications of these concepts, stemming from a badly understood recall of the information received during instruction.

In a psychogenetic study of the ideas that influence the concept of field, Nardi and Carvalho (1990) interviewed 45 Brazilian students on four cases of electrostatic interaction phenomena, one of which consists of an electrostatic pendulum attracting a positively charged rod. They show that the students' answers can be classified into three levels: (a) students that do not understand action at a distance and do not manage to relate the results of the experiment to a single cause, (b) students that attribute the action to the existence of forces at all points around a generating force that depends on the distance and that consider the field as represented by a vector magnitude with direction and meaning and (c) students who recognise that the field is a vector and discuss it correctly as such in different contexts and also use a scientific language that coincides with the theory taught at secondary level (ages 16–18). The authors suggest similarities between the classification obtained and the historical development of the field theory. They propose using historical development of field ideas both to identify issues in learning as well as a guide to helping students move from one interpretation to another.

Törnkvist and colleagues (1993) administered a questionnaire related to the electric field and its graphic and mathematical representations to over 500 university students. They found that 85 % of the students believed it possible that two field lines could intersect, 49 % believe that field lines can form an angle and 29 % consider that electrical field lines can be circular. The authors suggest that these poor results are a consequence of students' "naive" conceptions of the electric field which are based on intuition rather than on what has been explained in class. According to the authors, students tend to treat the field lines like isolated entities in a Euclidian field rather than as a set of curves that represent a physical property of space that has a mathematical representation. This "naive" way of reasoning and representing the electric field is also supported by the results found in the study by Galili (1995), previously mentioned. Pocovi and Finley (2002) studied the conceptions of 39 college students regarding field lines that support the aforementioned conclusions. They found that many students considered field lines as material entities that are capable of transporting charges and impose the path that the charges must follow.

Studies by Viennot and Rainson (1992) and Rainson and colleagues (1994), involving over 100 university students from France and Algeria, showed that the vast majority had difficulties in applying the superposition principle and in interpreting the electric field in a material medium. The authors believe that these difficulties are due mainly to a limited comprehension of the mathematical equations and mistaken reasoning relating to the causality of the phenomena. A high percentage of students related the fact that the charges did not move or the insulating nature of the matter with the fact that an electric field did not exist. The results suggest that students need to imagine an effect (movement of charges) to accept a cause. Another detected difficulty is linked to a causal interpretation of the formula. The study was carried out in relation to the expression of electric field around a conductor given by Coulomb's theory. The authors partly attribute the students' learning difficulties to a deficient and confusing pedagogic treatment of electric fields. In particular, they insist that the superposition principle for electrical interaction is a long way from being clear for the students and that it is useful to work on it in static situations before analysing electric circuits (Viennot and Rainson 1999). In addition, teaching must highlight the explanation of the causal aspects of both electric field and electric force. The authors propose that this focus should be unified both in electrostatics and electrical circuits.

Furio and Guisasola (1998) investigated Spanish students' difficulties on understanding the concept of electric field at high school and university level. They based their work on the hypothesis that historical problems in the development of the electric field theory relate to students' difficulties in understanding this concept. They found that most students do not use correctly the field concept and instead reason based on the Newtonian model of "action at a distance". These difficulties can be due to a linear, accumulative presentation of electrostatics in traditional teaching, teaching that does not consider qualitative leaps within the development of the theory. In a later study, Saarelainen et al. (2007) show that some students' difficulties are also related to the mathematical methods required and to the meaning of the field concept in electricity and in magnetism.

Kenosen and colleagues (2011) found that students do not include the vector nature of field quantities in their reasoning. In addition, students described the direction of the force interaction instead of the electric field. Some of the students were unwilling to apply the field concept in their reasoning. Authors state that this problem may result from the well-known difficulty that involves shifting students' understanding from the particle-based Coulombian conceptual profile to the field-based Maxwellian one.[1]

5.1.2 Students' Difficulties in Learning Electrical Potential and Electrical Capacitance

One of the most researched concepts in teaching electricity is electrical potential. The majority of these studies have focused on learning this concept in the context of electrical circuits, but from the 1990s onwards, more works emerged analysing this concept in the context of electrostatics and how it relates to electrical circuits. Eylon and Ganiel (1990) found that electrical potential is one of the concepts giving students the greatest learning difficulties when interpreting electrical circuits. They attribute this difficulty to the fact that the electrical circuits are described in terms of "macroscopic" variables (current, resistance, voltage measured by the voltmeter) whilst the explanations use models (charges, fields, potential). Such models relate concepts studied in electrostatics with those coming into play when analysing electrical circuits. The study shows that it would be a good idea to explicitly relate concepts such as electric field and electric potential studied in electrostatics with those in DC circuits.

It is well documented that secondary and first year university students are not capable of establishing relations between the concept of potential in electrostatics and their application in electrical circuits (Benseghir and Closset 1996; Cohen

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[1] Furio and Guisasola (1998), Rainson et al. (1994), and Viennot and Rainson (1992).

et al. 1983). This lack of relation means that the concept of electrical potential remains vague and is only used as a calculational convenience. Many students use the concepts of electrical potential and potential difference without a consistent meaning in an explanatory model (Shaffer and McDermott 1992; Shipstone et al. 1988), and, based on an incorrect use of Ohm's law, consider that if there is no current between two points in a circuit, there is no potential difference. This suggests that students think that the potential difference is a consequence of the flow of charges rather than its cause (Periago and Bohigas 2005; Steinberg 1992). In addition, Cohen et al. (1983) found that the battery of a DC circuit is conceived by the students as a device that supplies "constant current" rather than one that constantly maintains the potential difference between its poles. Many students confuse the concept of potential difference with the quantity of electrical charge (Thacker et al. 1999).

Guruswamy and colleagues (1997) show that students analyse the passing of charges between two conductors joined by a conducting wire looking at the quantity of charge in each conductor and not taking into account the potential difference between them. Guisasola and colleagues (2002) carried out a study on how freshmen students learn the concept of electrical capacity. The majority of students do not grasp the concept of potential of a charged body and identify its capacity with the quantity of charges that it accumulates. This prevents them from giving the right explanation of the phenomena such as bodies being charged by induction. In a study with secondary and university students, Benseghir and Closset (1996) show that for some students the potential difference between the terminals on a battery and the current circulation are not related: the potential difference is considered strictly numerically as a characteristic of the battery, and the electrical current is analysed from an electrostatic point of view (attraction between charges, different sign of the charges on either end, etc.). A significant number of students only consider that there exists a potential difference between the points of the circuit whenever the difference in signs is perceived (positive pole and negative pole) or when there is a variation of the quantity of charges between the points (within the resistor there is no variation in the quantity of charge). Students consider the potential difference as "abstract" and prefer a much more accessible concept such as electrical charge. It seems that when the students do not attribute meaning to these concepts, they take refuge in their operative definitions and base their reasoning on formulas with no meaning (Viennot 2001). In summary, the concept of potential is frequently presented in a purely operative way, and students are asked to make a leap through formal maths. This is where many of them fail.

High school and university students have difficulties when learning about electrical potential, due to the absence of analysis of electric circuits and its energetic balance. Most 3rd year physics students still do not clearly understand the usefulness of the concepts of potential difference and emf (Guisasola and Montero 2010). This shows the need to present potential difference and electromotive force to show that these measure different kinds of actions produced by radically different causes (Jimenez and Fernández 1998, Roche 1987; Varney and Fisher 1980).

5.1.3 Students' Difficulties in Learning DC Circuits

Research into teaching and learning about DC circuits points to students presented with a typical model for electric current as one of the charges moving between two points at a different electrical potential (charge flow model). Textbooks do not agree on the type of charges (positives or negatives) that are involved in the current. Charge flow presents serious difficulties for students. Closset (1983) showed that many secondary and university students analyse the circuit using "sequential" reasoning. Those students think that there are different entities ("current", "electrons" or "electricity") associated with intensity and tension that come out of the battery and are more or less affected as they pass through each element of the circuit, for example, "the current is used in the resistor" or "the current is spent in the bulb" without reference to what might have happened to the "current" before the element under analysis. They also do not consider how the "current" returns to the other pole of the battery. In addition, other studies found that secondary students believe that the current is spent as it passes through a bulb or that the current provided by the battery is independent of the topology of the circuit. Secondary students have difficulties interpreting the behaviour of resistors connected in series and in parallel in a complete DC circuit. The students find it difficult to accept that when the number of resistors in parallel increases, the total resistance decreases. They also fail to understand the relations between current and resistors and resistors and potential difference (Liegeois and Mullet 2002).

Concepts of electrical potential and potential difference are frequently confused with current intensity or energy. These concepts are taken to represent the "strength" of a battery. In addition, students frequently do not understand that the potential difference between two points in a circuit depends on its topology. Smith and van Kampen (2011) investigated pre-service science teachers' qualitative understanding of circuits consisting of multiple batteries in single and multiple loops. They found that most students were unable to explain the effects of adding batteries in single and multiple loops, as they tended to use reasoning based on current and resistance instead as on voltage, that thinking of the battery as a source of constant current resurfaced in this new context and that answers given were inconsistent with current conservation.

Borges and Gilbert (1999) study of explanatory models of electrical circuits showed that secondary students present alternative models such as "electricity as flow" and "electricity as opposing currents" where the electrical charges that make up the current are not taken individually. These models are barely concerned with the nature of electricity and essentially descriptive. Both models are very limited in terms of predicting the behaviour of the electrical current in the circuit. Borges and Gilbert (1999) show that we find more complex explanatory models in students in their last years of secondary school and at university level. For example, they think of electricity as "moving charges" or as "field". These models are capable of explaining some phenomena related to electrical currents, such as a relationship between the intensity of the current and the battery's potential difference. Greca and

Moreira (1997) show that the students' models for explaining electricity become more complex over the years of instruction but for most continue to be far from the scientific model.[2,3]

5.1.4 Summary of Research Findings on Students' Difficulties

Most of the mentioned difficulties seem resistant to traditional teaching of electrical circuits. Therefore, over the past decades, a great effort has been devoted to understanding students' conceptions before and after instruction. As a result, we have today some conceptual understanding on key electrical concepts:

- Students find it difficult to interpret electrical induction and polarisation phenomena using Coulomb's explanatory model for action at a distance.
- Most students from the last years of secondary school and university do not understand the ontological difference between "action at a distance" and the "field model". This leads to confuse the concept of field with that of the force that is exerted on the electrical charges and therefore not taking into account the medium where the interaction takes place.
- Students use inappropriate causal analysis to interpret equations such as the superposition principle.
- Many students confuse the electric field with the imaginary field lines that are used to represent it. Students state that the electric field exists only along the field lines and do not think of it as existing in every point in space.
- Students have a confused meaning of the concept of electrical potential and potential difference, leading them to avoid to use these concepts to analyse the movement of charges in a conducting wire.
- Students attribute the passing of electrical current to the difference in quantity of charge between the ends of a conductor.
- Students "take refuge" in operative definitions ("formulaic solutions") to analyse electrical phenomena. They usually base their reasoning on a literal description of the "formula" or an incorrect causal analysis of it.
- Most students think that electric potential as defined in electrostatics is different from the electric potential as defined in electric circuits.
- Most students do not relate macroscopic phenomena (electrical attractions and repulsions, electrical current, voltage of battery, etc.) with the microscopic concepts which build the explanatory theory (field, potential difference, polarisation, etc.).
- Most students in their analysis of simple electric circuits think that current is used up in a resistance; drifting electrons push each other through a wire just as water molecules push each other through a pipe; they confuse the Kirchhoff

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[2] Barbas and Psillos (1997), Cohen et al. (1983), Dupin and Joshua (1987), McDermott and Shafer (1992), and Shipstone et al. (1988).

[3] Duit and von Rhöneck (1998), Psillos et al. (1988), and Testa et al. (2006).

loop rule and Ohm's law (although Kirchhoff's law is a much more general principle), assuming that electromotive force and potential difference are synonymous.

As a result of these efforts to identify students' learning difficulties, greater attention should be given to conceptual understanding in physics programmes and textbooks (see, e.g. Engelhard and Beichner 2004; Halloun and Hestanes 1985; Maloney et al. 2001; www.ncsu.edu/per/testinfo.html).

More research is needed on students' conceptions in other areas such as capacitance and its relations with electrical potential, the movement of charges and electrical potential in a more complex electrical system.

5.1.5 Possible Reasons Underlying Students' Alternative Conceptions

Traditional teaching does not appear to improve students' lack of understanding of the electric field. There is a wide gap between the student's thoughts and this abstract concept (Furio and Guisasola 1998; Viennot and Rainson 1999). Some other reasons frequently suggested are:

- Poor knowledge of the mathematical tools demanded by the operative definition and its application (vectors, derivates and integrals)
- Poor knowledge of the basic concepts in the area of mechanics (force, work and energy)

In teachers' "spontaneous thinking" (Hewson and Hewson 1988), students are often blamed for these problems. Most teachers refer only to students' deficiencies to account for the general failure in learning, but the sort of teaching responsible should also be considered. Research into students' ideas and ways of reasoning identifies subject matter that must be better taught so as to improve understanding (Furio et al. 2003; Viennot and Rainson 1999).

Teachers' conceptions show a wide range of viewpoints concerning the teaching of DC circuits. Some viewpoints are consistent with alternative views of the students themselves like "straightforward" ideas on how circuits operate (Gunstone et al. 2009). In a study on the metaphors that experts and amateurs use when explaining electricity, Stocklmayer and Treagust (1996) found that "the teachers had a mechanical model which gave rise to images of electrons as small balls moving along tunnel-like wires" (ibid., p. 171). This conception contrasts with the experts' mental image that "was more global and holistic than the mechanical electron view. Essentially, these practitioners were concerned with the circuit as a whole" (ibid. p. 174). On the other hand, teachers frequently use scientific vocabulary to refer to how electrical phenomena work, but concepts such as electrical potential, potential difference or electrical field are avoided or misunderstood (Mulhall et al. 2001).

Many textbook presentations of these concepts are dominated by mathematical instrumentalism and simplification in justification. For decades (Moreau and Ryan 1985), studies on presentation of the concepts of electricity in textbooks indicate that many books do not pay attention or emphasise the connection between electrostatics and electrical circuits. For example, the fact that electrical potential in circuits is exactly the same as in electrostatics is not highlighted, assuming that the students make the connection themselves. Heald (1984) claimed that there is a discontinuity in the presentation of the topics of electrostatics and DC circuits in introductory physics courses. In electrostatics, the analysis focuses explicitly on the electrical charges in the bodies and on the electrical field and potential in space and matter. In the following chapter on DC circuits, attention focuses on batteries, resistors, conductors and condensers. In the 1990s, Stocklmayer and Treagust (1994) carried out a study on the ways that textbooks presented the concepts of electricity in the period 1891–1991 and found that despite the fact that the historical development of the electromagnetic theory made important qualitative jumps towards a modern understanding of electrical current in a circuit, there are few changes in this regard in the analysed texts. Most represent the electrical current as the movement of a fluid – a pre-Faraday image. In addition, Bagno and Eylon (1997) found that many textbooks present an electrical field as a force to be applied on the electrical charges; this idea might lead students to misunderstand this difficult and nonintuitive concept.

Researchers agree on students' scant learning concerning electricity; however, there is a lack of consensus about specific learning targets for electricity. For example, Shaffer and McDermott (1992) focused on electric current, Licht (1991), Psillos (1998) and Psillos and colleagues (1988), emphasised potential difference whilst Eylon and Ganiel (1990) and Sherwood and Chabay (1999) focused on a microscopic-oriented approach. The lack of consensus results from the vast number of aspects such as the nature of the models and analogies that are considered appropriate when teaching electricity, the nature of the very concepts that can be used at each level and the relationship between the world of phenomena at a macroscopic level and the explanatory theories at a microscopic level (Dupin and Joshua 1989; Härtel 1982). The nature of the models and analogies that each teacher chooses are intrinsically linked to the teacher's understanding of the concept (Duit and von Röneck 1998; Pintó 2005). Therefore, it is necessary to define the conceptual and methodological aims of the teaching sequences in electricity. A careful reflection is required in order to justify, from a theoretical framework of physics teaching, "what" to teach and "how" to go about it. Both aspects are interrelated and require conceptual and epistemological analysis even in elementary aspects. Contributions to these problems from history and philosophy of science and the current theoretical framework of physics are reviewed in the next section.

5.2 The Contribution of History and Epistemology of Science to Teaching Electricity

Scientific concepts and theories do not emerge miraculously but are the result of an arduous process of problem solving and a rigorous testing of initial hypotheses (Nersseian 1995). In science, dynamic change and alteration are the rule rather than the exception (Thackray 1980). Quoting Kuhn (1984): "I was drawn … to history of science by a totally unanticipated fascination with the reconstruction of old scientific ideas and of the processes by which they were transformed to more recent ones" (ibid. p. 31). Knowing how explanatory ideas lead towards the current scientific model can provide important information when setting learning targets and selecting knowledge that helps to design teaching sequences (Duschl 1994; Wandersee 1992). The history of science is a useful instrument when teaching sciences, specifically electricity, to identify problems encountered in building concepts and theories, which epistemological barriers had to be overcome and which ideas led to progress. Furthermore, history of science can show the social context where theories were developed and the technological repercussions that resulted from the acquired knowledge.

Current consensus states that understanding concepts and theories requires knowledge not only of the current state of understanding of a particular topic, but also of the way that knowledge has been developed and refined over time. Moreover, educational standards developed in the last decades (National Research Council 1996; Rocard et al. 2007) call for a presentation of concepts and theories involving not only a historical perspective but also a meaningful introduction of terms and an appropriate representation of the social and scientific context of the origin of the key ideas and solutions.

The structure of science, the nature of the scientific method and the validation of scientists' judgements are some of the areas in which history and philosophy of science can enrich the teaching of science. There are many arguments defending the inclusion of history of science in the curriculum, particularly its integration in teaching strategies. This section considers the history of science as a useful instrument for identifying problems in the construction of concepts and theories and for indicating the epistemological barriers that had to be overcome and the ideas that permitted progress to be made (Furio et al. 2003). By building on this information, teaching objectives can be drawn up that might help in designing teaching sequences that will significantly improve the teaching and learning of concepts and theories (Mäntylä 2011; Niaz 2008). Nevertheless, in order for this information to be useful in the design of a didactic sequence, it requires a historical and epistemological study to be carried out with "pedagogical intentionality" and knowledge of students' learning difficulties. A critical study of the history and epistemology of science (where history is seen as a source of solved problems leading to advances in scientific knowledge) is likely to show teachers and researchers qualitative leaps in the evolution of a concept. To consider these "discontinuities" between meanings of concepts and models may help to clarify, explain and explore physics concepts and understand students' learning difficulties.

The history of electricity shows the most important epistemological and ontological difficulties in the development of the theory of electricity that researchers had to overcome to arrive at today's conceptual framework of electricity. Because the concepts of electricity are abstract and quite remote from students' spontaneous ideas, the historical perspective can be important in terms of making decisions regarding teaching sequences and objectives. Conceptual changes in science could provide some insight for contemporary instruction of science. However, there are obvious differences in the reasoning processes of current students and past physicists to be taken into account in teaching.

5.3 The History of the Evolution of Theories About Electricity During the Eighteenth and Nineteenth Centuries

William Gilbert, partly compiling J. Cardan's ideas published in "De subtilitate" (1550), established a clear division between the effect of amber and magnetism in his book "De Magnete, Magneticisque corporibus, et de magno magnete tellure" (1600). With the use of the "versorium", Gilbert carried out the first classification of "electric" and "nonelectric" materials. Gilbert explained that these phenomena were due to "material nature" freed on rubbing "electric" bodies such as glass or amber. At that time, Gilbert's "effluvia" model was used to explain electric attraction between bodies charged by rubbing. It was also used in the classification of bodies into "electric" and "nonelectric" depending on whether they became charged when rubbed and electrical discharges in rarefied gases or induced "glows" (Whittaker 1987). This explanatory model of "electric effluvia" failed to give plausible explanations for new electric phenomena such as electric repulsion or electric transmission. After Gray's discovery of electrical movement, it was not possible to accept the effluvia were inseparably joined to the bodies from which they had flowed through rubbing. It had to be admitted that outflows had an independent existence, as it was possible that they were transferred from one body to another. Therefore, these effluvia were acknowledged under the name of "electric fluid" as one of the substances that made up the world. Du Fay's and Franklin's contributions, among others, were to confirm a model that described electricity as an electric fluid made up of extremely subtle particles. The "electric fluid" model did not explain why two bodies which lack fluid (negatively charged) repel each other and it also had some difficulty in explaining induction. Towards the final third of the eighteenth century, it was thought that quantitative foundations were needed to advance the study of electricity. Thus, researchers such as Cavendish, Priestley and Coulomb looked for a theory similar to gravitation, under the clear influence of Newtonian mechanics (Conant et al. 1962; Harman 1982).[4,5]

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[4] Duschl (2000), Matthews (1994), McComas et al. (2000), Rudge and Home (2004), and Wandersee (1992).

[5] Clough and Olson (2004), Izquierdo and Aduriz-Bravo (2003), Seroglou et al. (1998), and Solomon (2002).

The new model that emerged at the beginning of nineteenth century is coherent with Newton's physics, in the sense that it introduces notion of "action at a distance" forces, which operate instantaneously between charged bodies. The interactions are central forces, calculable by means of Coulomb's law. With the law on the conservation of charge and Coulomb's law on the attraction of charged bodies, electricity was raised to the level of "modern science". The result was that the "action at a distance" theories became almost the only focus of attention, until much later, when Faraday led electrical theory towards more complex and fruitful explanations using the concept of field lines (Whittaker 1987).

During the nineteenth century, different discoveries showed that the Coulomb model of interpreting electromagnetic phenomena had to be rethought. Oersted showed experimentally that "transverse actions" existed between an electric current and a compass, as opposed to the concept of central forces for all actions at a distance Wise (1990). The role of the surroundings in which the interaction took place also began to be emphasised by new experimental facts, e.g. it was found that containers with air pressure maintained the charges better on a conductor (Berkson 1974; Cantor et al. 1991). Volta's discovery produced a continuous electric current by setting up different materials in a certain order. These findings, among others, were to provide evidence to support the unity of natural forces (Sutton 1981). The law of the conservation of energy, formulated in 1840, placed the phenomena of light, heat, electricity and magnetism into a framework of general principles.

After Volta, different explanations appeared as to how an electrical circuit might operate. For decades, the concept of "electrical circuit" phenomena was linked to electrostatics (Benseghir and Closset 1996). The "electrical fluid" and "electrical conflict" models were used to explain the neutralisation of charges in batteries and other materials. The analysis of electrical circuits is closely related to the analysis of the electrical charge accumulation processes, studied during the eighteenth century on charges and discharges in isolated bodies (Leyden jar). The invention of the voltaic cell and the apparently perpetual movement of the electric fluid brought about changes in the theoretical frame. This led to defining the electric potential of a charged body and the concept of capacitance, as it is conceived today. The concept of electrical potential, used to explain how circuits work, was another challenge for scientists in the nineteenth century. However, as Roche (1989) states:

> The concept of potential is the fusion of at least five quite distinct historical traditions. Despite the seeming unity of the received concept, each of these traditions still plays a semi-autonomous role in the present-day understanding of potential. (p. 171)

This is a crucial point in clarifying and explaining the electrical phenomena in electrostatics and in circuits.

Alessandro Volta attempted to establish that the "galvanic fluid", of animal origin, was the same as ordinary electricity or static electricity (Kipling and Hurd 1958). In the midst of the controversy regarding the nature of electricity, Volta discovered that when two uncharged bodies of different metals were brought into contact, either directly or by means of an electrolyte, the two metals in a closed circuit acquired a charge and remained charged despite the presence of a conducting path where charges could flow and thus neutralise each other (Brown 1969; Fox 1990; Sutton 1981). This is a clear break with the idea that opposite charges could not be separated, as believed within the electrostatics realm at this time. Volta introduced the concept of "degree of electric tension" of a charged conductor and also defined "electromotive force" as the prime mover of current in a closed circuit, measured as electric tension. He stated that a new type of "force" was acting upon the charges, separating them and keeping them separated, and he called this action the electromotive force, the name that is still applied (Pancaldi 1990; Willians 1962). Volta's explanations did not fit into Coulomb's paradigm which prevailed in the first third of the nineteenth century. In this "electrostatic" context, the concept of "electromotive force" was interpreted as the capacity of bodies to generate electricity in others. Thus, one of the metals in the Volta battery "generates" electricity in the other due to its "electromotive force". Volta's interpretations regarding how batteries work did not fit into this theoretical framework and dropped into oblivion (Warney and Fischer 1980). These primitive concepts refer directly to mechanical-type analogies, emerged later on in the nineteenth century: "electric pressure" or "force" is thought of as a property of the electric fluid and not of continuous space.

S. D. Poisson and G. Green in 1811 introduced a very different meaning of the concept of electrical potential in electrostatics as a mathematical function whose gradient was the numerical value equal to the electrical intensity or force per unit of charge. First thought of only as a mathematical construct (Fox 1990), Green named this function "potential".

In 1827 Ohm made a contribution to circuit theory through his law for conductors. Ohm clarified the separate and complementary roles of current and potential at a time when both were rather confused. He supposed that a stationary gradient of volume charge corresponding to a gradient of potential drives a steady flow of electricity. Ohm used the analogy of temperature gradient driving heat transfer for explaining electricity flow (Schagrin 1963; Taton 1988). G. Kirchhoff who synthesised Ohm's work on electrical conduction and electrical resistance made the greatest step in the development of the concept of potential and circuit theory. On the basis of what was known about electrostatics, there could not be a gradient of volume charge inside the conductor, and Kirchhoff solved the problem putting a gradient of charges on the surface (Whittaker 1987). Kirchhoff demonstrated that Volta's "electrical tension" and Poisson's potential function were numerically identical in a conductor and therefore could be reduced to a single concept. Thus, he showed that electrostatic and circuit phenomena belonged to one science, not two (Heilbron 1979). From this unification the role of potential came to dominate the analysis of circuits but without attention to surface charge distribution.

Explanatory models of electrical current received a new impulse with the theory of fields initiated by Faraday and developed later by Maxwell in 1865. The field model suggests an ontological change in conceiving electric interaction, without test charges proving its existence, and introducing potential energy into the theory of the field. Maxwell (1865), referring to the "positional" character of the vector intensity of electric field in *A Dynamic Theory of the Electromagnetic Field,* showed just how difficult this model is:

> On talking about the intensity of the electric field at one point, we do not necessarily assume that a force is really exerted there, but just that, if an electrified body is set there, a force will act on it … that is proportional to the charge of the body. (p. 17)

Faraday's field theory also involves a new conception of electric interaction, where its representation is not limited locally to the charged material particles, but rather spreads around the surrounding space. Going deeper into the ontological change that takes place from Coulomb's vision to that of the electric field, in the former, the concept of electric interaction is linked to that of charges in a zone of the space or in a charged body; there is no electric interaction without the electric charges that interact in the space. Moreover, the new understanding of the electric field forces us to think in a different way, as the concept of electric interaction is no longer linked to two electric charges, but rather extends along the area of influence for one of them. If the electric field is considered as a property of each point in the space, the electric action can "be" without the need of charge. From this new conception of electrical interaction, it is easy to establish the relationship between the concepts of charge, electric field and electric potential energy.

Physical properties can help explain the difficulties to understand some of the concepts used in electricity. One topic for discussion among physicists has been the meaning of the concepts of potential, potential difference and electromotive force. Härtel (1985) indicates that the majority of textbooks define potential in abstract and mathematically elegant ways but discard any causal mechanisms that explain the flow of electrons in electrical circuits. He finds it necessary to give meaning to the concepts of potential and potential difference.

Reif (1982), Romer (1982), and Peters (1984) discuss electrical potential, potential difference and electromotive force in the context of electrical circuits. Their studies conclude that the voltage measured by a voltmeter is equal to the total work per unit of charge moving through the instrument. Since the voltage indicated by a voltmeter depends on both Coulomb and non-Coulomb forces within the instrument, the voltage measured is generally different from the potential difference between the points to which the leads of the voltmeter are connected (voltage is equal to $\Delta V + \varepsilon$).

In addition, some early 1950s and 1960s textbooks showed surface charges on the wire as the cause of the electric field inside the wire that produces the electric current flow (Jefimenko 1966; Sommerfield 1952). Rosser (1963, 1970) described a mathematical analysis of the electric field produced by the wires surface charge distribution, which is of great value in understanding the electric field in electrical circuits. Härtel (1982) proposed analysing the electric circuit as a system. In this approach, the three fundamental terms current, voltage and resistance are introduced simultaneously in a qualitative way. The term voltage is introduced in close relationship to the cause of the motion. However, Härtel stated that for a complete understanding of why there is a potential drop in order to move the charges between two points of a conductor, it is necessary to analyse the interaction between electric field and the charges carriers. In a later study, Härtel (1987, 1993) analysed the gradient of the charge distribution along the different parts of the circuit, which produces different electric field depending on the resistance of this part of the circuit. He discussed the relations among the usually disparate topics of electrostatics and circuits by means of the surface charges and gave students a qualitative understanding of circuit behaviour. He also discussed the transient behaviour of circuits when, for example, a switch is closed.

Other studies such as those carried out by Aguirregabiria and colleagues (1992) and Jackson (1996) confirm the utility of the gradient distribution of charges model to explain potential changes in the circuit. Chabay and Sherwood's book (2002) compiles, among others, Hartel's contributions and proposes to carefully consider the concepts of "surface charge and feedback". This proposal justifies the continuity between the concepts studied in electrostatics and in electrical circuits. In Preyer (2000) two lecture demonstrations are described which illustrate the point that electrical potential in a circuit is the same function of charge density distribution as it is in electrostatics.

Another recurring topic of discussion in the theoretical framework of physics is the use of the Newtonian and Maxwellian model of interpreting electromagnetic phenomena. It should be pointed out that the Newtonian and Maxwellian models when used to interpret interactions between charges can be considered as belonging to a different ontological and epistemological status, but not opposite. This means that the scientific community assumes them both, although the higher conceptual level and power of one of them is admitted. For example, when analysing the electromagnetic phenomena, it is possible to make a description in terms of the intensity of the field that exists in this zone of the space or in terms of the action that the field exerts on the charges that there are in this area of the space (the exerted force). However, as Sharma (1988) stated:

> To find out the force on a test charge q at a point in space, you do not have to go all the way to find out where the sources (charges or currents) are; instead, you just have to know the values of E and B at that very point and use the Lorentz force law to compute the force. If the E and B from two source distributions are the same at a given point in space, the force acting on a test charge or current at that point will give the same, regardless of how different source distributions are. This gives E and B meaning in their own right, independent of sources. Further, the finite speed of propagation of electromagnetic signals, the retarded action, requires fields to carry energy, momentum, and angular momentum in order to guarantee conservation of these quantities. (p. 420)

The Maxwellian framework is touted to be conceptually superior and has more explicative power. Nevertheless, constructing field theory requires previous acquisition of the old framework (i.e. it is not possible to introduce electric field without knowing the prerequisites of Coulomb's electric charge and force) and the acknowledgment of its theoretical insufficiencies (Berkson 1974).

Chart 5.1 summarises the different models used through history and today's classical electromagnetic framework to interpret the basic electric phenomena.

5.4 Concluding Remarks: Guidelines for Designing Teaching-Learning Sequences

In secondary teaching and introductory physics courses at university level, there are learning difficulties in areas such as a scientific model for electrical current in a circuit and in concepts such as electrical field and electrical potential. A lack of connection has also been observed between the same concepts taught in electrostatics and

Chart 5.1 Models to describe fundamental electric phenomena

Empirical reference	Different models used through history
	Effluvia model
Charging of bodies by rubbing	Electric phenomena were due to something ("electric effluvia") that was freed upon rubbing "electric" bodies such as glass or amber
Attraction between charged bodies	Methodology used criteria of empirical evidence for testing the theory
Attraction of light bodies by rubbed bodies	*Explanatory problems:* The model did not explain repulsion between charged bodies
	Electric fluid
Transmission of electricity or "electric property"	The model describes electricity as an electric fluid made up of extremely subtle particles. Electric fluid can be transmitted and is not inseparable from the charged body, as in the previous model. Rubbing does not create electricity; fluid is just transferred from one body to another. So, the total amount of electricity in any isolated system is invariable
Electrification by contact	The excess and lack of electricity of the body are associated to the + and −, respectively. The empirical rule according to which bodies charged with the same sign repel and those with different sign attract is defined
Electric repulsion phenomena	The electric fluid accumulated in the body exerts a pressure on the surface of the body. At a certain point, the "electric pressure" is big enough to prevent the body from admitting any more charge. The capacitance is defined as $C = Q/\text{tension}$
Electric induction	The current in a simple circuit was explained by the theory of "electrical conflict" based on the electrical fluid model
Electrical capacitance	*Explanatory problems:*
	The research methodology is qualitative. It can neither quantify the electrical phenomena nor define their magnitude
Electrical simple circuits	The model does not explain why two bodies, which lack fluid, repel each other
	The electric induction explanation by using the "electrical atmosphere" is questioned by means of experimental evidence
	The role of battery in a circuit is still unexplained
	Action at a distance model
Electrostatic phenomena	A quantitative methodology, similar to that used in Newtonian mechanics, is introduced, and the concept of electrical charge is defined through the formula of electrical force. The model describes electricity as a set of charges that interact at a distance, in agreement with Coulomb's law. Electric interaction between separate charges is transmitted instantaneously through the space where they are situated, whatever medium exists between them
Condensers	The capacity of the charges to act at a distance implies the presence of an electrified body near the body to be charged and involves some modification in the electrical potential of the system and its "capacitance" to store charges. The capacitance is a property of conductors that interact
Simple electrical DC circuits	Direct current is due to the flow of electrons under the influence of electrical forces and under the influence of a potential difference across the poles of a battery

(continued)

Chart 5.1 (continued)

Empirical reference	Different models used through history
	Field model
Electrostatic phenomena	In this new understanding of electric interaction, not only charges but also the medium is taken into account. The interaction's transmission is non-immediate, because it depends on the medium existing between the charges
Electrical capacitance	The process of charging a body implies work and the acquisition of an electric potential. Thus, the concept of capacitance is a property of the system of conductors that interact which can in principle be measured as $C=Q/\Delta V$
Electrical potential energy Simple electrical DC circuits	Electric currents in wires, resistors, etc. are driven by electric fields. The electric field has its source only in the surface charge distributions on the wire

in circuits. The review points to problems that need to be addressed when dealing with the Maxwellian model of electricity. Following the recent educational standards' recommendations on presenting concepts and laws in a contextual meaning (National Research Council 1996; Rocard et al. 2007), some of the discussions among physicists on teaching field and electrical potential topics to secondary and university students have been pointed out. The contributions from physics education research and from the history of science should be taken into account by teaching staff and curriculum designers.

The traditional curriculum for teaching electricity at secondary schools starts by analysing how electrical circuits work. Many teaching activities are centred on analysing circuits with resistors arranged in series and in parallel by means of Ohm's law. The circuit is often not explicitly analysed in terms of its energy and of the role played by the battery's electromotive forces and movement of electrons.

The focus on resistors (Ohm's law) can lead many secondary and first year university students to think that Ohm's law is a fundamental law of electricity. As Bagno and Eylon (1997) states: "A high proportion of students considered Ohm's law to be one of the most important ideas of electromagnetism, consistent with previous findings, labelled humorously 'the three principles of electromagnetism': $V=iR$; $i=V/R$; $R=V/i$" (p.731).

In secondary education (Steinberg and Wainwright 1993) teaching about DC circuits and the role of the battery, use the compressible-fluid model – pressure gradient driving the current – for charge conduction. This pressure gradient results from a gradient in the charge-carrier volume density. However, according to conventional physics, electric current in DC circuits is driven by the electric field, created by the surface charge distribution. The volume charge density inside the wire is zero. As Mosca and De Jong (1993) show, this model can lead to erroneous conclusions:

> An erroneous conclusion associated with the compressible-fluid model is that it predicts the existence of an electric field within a charge conductor in electrostatic equilibrium.

> According to this model, the region within the material of an isolated charged conductor in electrostatic equilibrium is occupied by a gas of charge carriers that is uniformly compressed to a high number of density- and thus charge density. In accordance with Gauss's law, any nonzero charge density is necessarily accompanied by an electrostatic field, and the presence of this field contradicts the widely accepted view that a conductor in electrostatic equilibrium is an equipotential. (p. 358)

One can argue that a misconception in the electrostatic realm is not necessarily a misconception in circuit theory. However, the compressible-fluid model can lead to misconceptions not only in electrostatics but also in DC circuits (Mosca and De Jong 1993, p. 358). Moreover, in classical physics, electrostatics is part of electrodynamics as, e.g. analysing a DC circuit containing a capacitor (Guisasola et al. 2010).

The traditional approach changes completely when the concept of electric potential is introduced in senior high school (16–18 years old) and introductory physics courses at university. At these levels, the concept of electric field is first introduced and defined as $E = F/q$, electric potential at a point as the energy per electric charge ($V = E/q$) and potential difference between two points as the quantity of energy required or supplied to move a unit of charge from one point to another ($\Delta V = \Delta E_p/q$). All these definitions are made in an electrostatic context so that later in the study of electric circuits, the same concepts can be used again when applying the principles of charge and energy conservation (Kirchhoff's laws). However, textbooks frequently do not show explicit relations using these concepts in both contexts (Stocklmayer and Treagust 1994). As demonstrated in the previous sections, the research into teaching electricity and the history of science shows that the explanatory model of electrostatic phenomena conditions how we see the electric nature of matter and the flow of current in a circuit.

Recent studies propose starting the electricity curriculum with elementary electric phenomena (electrification by friction, contact or induction) and focusing students' attention on the microscopic explanatory models to improve students' understanding.[6] These proposals recommend the representation of models based on energy and field, allowing students to interpret at a microscopic level the electric phenomena observed at a macroscopic level (Walz 1984). For example, when a pendulum repels, a small positively charged ball from a positively charged rod, the work done results in an increase in the ball's gravitational potential energy. This work corresponds to the change in electric potential energy associated with a given configuration of the system (Borghi et al. 2007). The phenomenon is explained using an energetic model instead of an equivalent force model. In this approach, the other parameter required to define the energy of a system is its capacitance. The system's electrical status can be described by a new physical property "capacitance" that expresses the system's ability to receive more electric charge (Guisasola et al. 2002). This quantity can be used operationally by relating the capacity of the charge and the electric potential. The analysis of electrostatic phenomena in terms of

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[6] Benseghir and Closset (1996), Eylon and Ganiel (1990), Furio et al. (2004), Park et al. (2001), Thacker et al. (1999), and Viennot (2001).

energy relationships encourages the development of a relationship between electrostatics and circuits (Arons 1997).

Härtel (1982, 1993) proposed a transition from electrostatic to circuits, based on the electric circuit as a system. The students' tendency to reason locally and sequentially about electric circuits (Duit and von Rhöneck 1998; Shipstone et al. 1988) is directly addressed by analysing the behaviour of the whole circuit. The three fundamental terms (current, voltage and resistance) are introduced simultaneously in a qualitative way using the energy balance of the whole circuit including possibilities of transporting energy and the concept of potential energy.[7] At secondary school level, the aim should be to help students understand how elementary circuits work instead of quantitative circuit analysis (Kirchhoff's laws). This involves linking the movement of charges between two points of a conductor to the concept of potential difference and the transition from the potential of static charges to the DC circuit in a stationary state. The role played by the battery is here a critical point. As Benseghir and Closset (1996) state: "it must be pointed out that the battery keeps a constant difference of potential between its terminals" (p. 181).

Chabay and Sherwood (1995, 2002, 2006) propose a field model unifying electrostatics and circuits, which relates field and potential to DC circuits as suggested by Härtel. This is a microscopic model of the electric current based on the change in the surface density of charges generating an electric field in the direction of the wire. The function of the battery is to maintain the surface density of charge that is caused by the electric current inside the wire. Understanding macroscopic phenomena requires a coherent model of microscopic processes (Thacker et al. 1999). Students' difficulties in qualitative analysis of electric circuits can be overcome with more emphasis on microscopic processes. The proposal for teaching electric current based on the field model explicitly relates the measurements at a macroscopic level (voltage and current intensity) with a causal model at a microscopic level that uses potential difference and constant speed of electrons to explain the macroscopic measurements. Moreover, the role played by surface charges in DC circuits can show to students by a graphical method developed by Muller (2012).

Chabay and Sherwood's programme, after going through various sequences, has been successfully used in first year introductory electricity and magnetism physics courses at university (Ding and colleagues 2006). Students taught with this scheme were able to analyse circuits in a significantly better way compared to students in traditional courses. In introductory physics courses at university, teaching DC circuits theory using the field model has also been successful in other countries (Hirvonen 2007). At high school level, the preliminary findings indicate that this approach may be more successful than the traditional electron flow model (Stocklmayer 2010). Furio and colleagues (2003) found that high school students whose teaching included electric field concepts showed an important improvement in their understanding of electrostatics. Correct results from these students were at least 50 % better than from the control group, with statistically significant results in all comparative tests.

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[7] Cohen et al. (1983), Duit (1985), Härtel (1985), Psillos (1998), and Psillos et al. (1988).

Saarelainen and Hirvonen (2009) show that understanding the electric field concept is necessary for comprehension of electrostatics and particularly Gauss' law. Performance in this area can be improved by taking into account students' thought processes and applying methods suggested in educational reconstruction. Silva and Soares (2007) looked at results from the use of an electrical field and potential energy model by 2nd year students in a teacher education course in Portugal. The aspect of this model proved fruitful in bridging electrostatics, DC and AC circuits. At secondary school level, Psillos (1998) and Psillos and colleagues (1988) proposed a model based on potential energy to explain the relations between macroscopic phenomena in simple DC circuits and the movement of charges at microscopic level. Their results show that the approach improves students' understanding of how current flows and the behaviour of the whole circuit.

It is recommended that use of these models should begin in the electricity curriculum in secondary schools as they address three key problems identified so far are:

(a) Relations between electrostatics and current
(b) Relations between macroscopic phenomena and microscopic level models
(c) Relations between operative definitions of charge, potential and electric capacity and their meaning in electrostatics and current

However, very few high school or basic university textbooks propose a qualitative electrostatics and circuits model based on field and energy. Although there is consensus among the research literature on the insufficiency of traditional treatments, the qualitative model remains on the margin of the usual mathematical treatment based on Kirchhoff's laws. Textbooks avoid a presentation that relates micro and macro views, possibly because surface densities of charge, small in normal DC and AC circuits, are difficult to measure in the laboratory. It appears obvious that a model based on the surface density of charge in the wire is not familiar to teachers and not easy to understand at these levels. Stocklmayer (2010) suggests the following changes in teaching:

> The problem with the universal adaptation of the field model lies in its unfamiliarity. It is not within the 'comfort zone' of many teachers, nor, indeed, many conventional physicist for whom the electron flow model has proved comprehensible and satisfactory … It will require the development of new resource materials, including textbooks and practical exercises, and extensive professional development for teachers. (p. 1825)

More research is needed on teaching sequences design based on new models and their implementation in the classroom. Lijnse and Klaassen (2004) argue that designing teaching sequences requires a complex process of applying didactics to specific teaching contexts, a cyclic rather than linear process aiming at generating knowledge about the relevance of improved teaching materials in the classroom.

In conclusion, this research offers guidelines and teaching experiences to teachers and curriculum designers for changes in the traditional system of sequencing electricity topics. Research and the history of science contribute evidence to strongly suggest that key points of the electricity curriculum should be covered differently.

Students should be given the chance to think about the use of the same electricity concepts in different contexts and about the relations between macroscopic observations and explanatory models at a microscopic level.

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Chapter 6
The Role of History and Philosophy in Research on Teaching and Learning of Relativity

Olivia Levrini

6.1 Introduction

With respect to topics of classical physics, special relativity has been subject to a limited number of studies in physics education research (PER). However, educational studies focusing on special relativity include some milestones in PER development since the latter have become established in a specific research discourse. The development of studies on relativity mirrors significant changes in research priorities that can be identified in science education research.

In this chapter the review of the literature concerning teaching/learning special relativity is carried out so as to sketch the story of research development in physics (science) education.

In the story particular attention is paid to reflection about the role of history and philosophy of physics in teaching/learning and to their contributions to a number of research strands, namely, conceptual change, students' difficulties, curriculum design, educational reconstruction and teacher education.

6.2 The Curricula of Reference

The story starts in the 1960s when Taylor and Wheeler (1965) and Resnick (1968) published two textbooks (teaching proposals) which became the main references for teaching special relativity both at university and at secondary school in the western world.

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In Italy Resnick's approach has been more popular in university courses and in textbooks for high school students. Taylor and Wheeler's approach has been chosen only by an élite group of teachers, even though the 1992 version of Taylor and Wheeler's book was conceived to be used by a wide range of students and teachers.

The two curricula focus on different concepts (relativistic effects or invariant quantities and relations), use different languages and reflect different interpretations of special relativity. Resnick's proposal presents the theory by following its historical development and in coherence with the operational approach ascribed to the original papers of Einstein; Taylor and Wheeler's proposal offers an elegant and conceptually transparent nonhistorical reconstruction of the theory, by relying heavily on a geometrical/Minkowskian formulation of special relativity.

More specifically, Resnick's proposal holds the thesis that relativity is 'a theory of measurement' and such a thesis is argued by focusing on Lorentz transformations, by using algebraic representations predominantly and by illustrating the physical meaning of the relativistic effects (relativity of simultaneity, length contraction and time dilation) by means of Einstein's thought experiments. Particular attention is paid to the experimental results that led to – and corroborated – the need for revising the conceptual bases of classical kinematics and dynamics.

The proposal of Taylor and Wheeler emphasises, by means of geometrical language, the concepts of event, space-time interval, energy-momentum and invariance. One of its main advantages is that it paves the way to contemporary physics, including particle physics and general relativity. Unlike the traditional approach and thanks to their decision to keep away from history, the authors make the puzzling choice of presenting, from the beginning, special relativity as a theory holding in absence of gravitation, that is, according to the equivalence principle, in free-floating frames of reference.

The success of Resnick's proposal is probably due, besides the clearness and coherence of the presentation, to the use of steps in the historical development of the special theory of relativity. Use of history is usually conceived as an effective teaching strategy for softening the impact of a theory that requires that space and time views be deeply revised (Holton 1973). Moreover the operational approach, although criticised by many physicists and philosophers as a simplistic form of empiricism, is accepted to have a great persuasive power because of the image of concreteness that it seems to give.

The main criticisms addressed to Resnick's approach concern the limits shown by the algebraic-operational language both when moving to general relativity and in highlighting the formal four-dimensional structure according to which new relations among the dynamical concepts of mass, energy and momentum must be redefined.

Despite its cultural relevance and conceptual transparency, the proposal of Taylor and Wheeler met more problems in its diffusion because of problems of implementation at the secondary school level. The main sources of problems are the 'length' of the outlined curriculum path with respect to the time that can be scheduled for relativity within the whole physics curriculum in high school and its unfamiliarity that teachers may find it difficult to compare it with the paths they followed as students or that are presented in textbooks.

These two authoritative curricula represent, in this paper, the reference both for discussing the main results obtained by research in teaching/learning special relativity and for roughly sketching the development of the research along the following macro-strands:

(a) The affirmation of learning as a process of conceptual change (§3)
(b) The issue of the image of physics and the need for rethinking the curriculum: the role of history and philosophy for designing teaching proposals (§4)
(c) The problem of disseminating innovation in school by means of teacher education (§5)

6.3 The Research on Conceptual Change

In his chapter in the *Cambridge Handbook of the Learning Sciences*, diSessa provides an interesting review of research on conceptual change and of its relevance in the learning sciences (diSessa 2006).

By taking 'History of Conceptual Change Research' as a reference, some studies focusing on teaching/learning special relativity can be selected as representative both of the development of this research strand and of the multiple perspectives which have been established in this multi-faced area:

- The milestone paper by Posner et al. (1982), which established the first standard in model of conceptual change
- Contemporary or follow-up papers, which analysed case studies (Hewson 1982) and proposed extensions, specifications and/or revisions of the model of Posner and colleagues (Hewson and Thorley 1989; Gil and Solbes 1993; Villani and Arruda 1998)
- Empirical studies (Villani and Pacca 1987) and thoughtful papers emblematic of the 'misconception movement' (Scherr et al. 2001, 2002), which allowed students' difficulties to be pointed out
- A paper representing the 'knowledge in pieces' perspective where a specific model of concept and conceptual change (the coordination class model) was used for analysing an extended classroom episode where students were coping with the concept of proper time (Levrini and diSessa 2008).

Beside their theoretical or methodological value that goes beyond the physical domain to which the examples refer, these papers show two important common features: they all focus on the same, or very similar, learning problems, namely, students' difficulties in accepting space-time implications of special relativity, and they all refer, more or less extensively, to the history of special relativity for designing successful teaching strategies and/or for explaining their success.

Therefore, the work of comparing and discussing the results is not only relatively simple but also suitable for stressing how the research developed, what stable results were achieved and what open problems are left.

The paper of Posner and colleagues represents a ‘landmark in the introduction of rational models of conceptual change: models that hold that students, like scientists, maintain current ideas unless there are good (rational) reasons to abandon them’ (diSessa 2006). In particular, the model proposes that students and scientists change their conceptual systems only when several conditions are met: there must be *dissatisfaction* with existing conceptions; a new conception has to be *intelligible,* to appear initially *plausible,* and it should suggest the possibility of a *fruitful* research programme (Posner et al. 1982).

One example reported by Posner and colleagues is a case study described more extensively in a paper by Hewson where he demonstrates the importance of the learner’s metaphysical commitments as components of the existing knowledge and where he explicitly suggests the effectiveness of instruction organised around that framework (Hewson 1982).

The discovered metaphysical commitments can be referred, in Hewson’s words, to a *mechanistic view* of the world. According to such a view, extended objects are assumed to have fixed properties (a fixed length), conceived the fundamental reality in nature, and any explanation of relativistic effects is given in mechanistic terms.

The strength of such metaphysical commitments is argued to be the main barrier which prevents the learner, whose interview is discussed, to accept the counterintuitive aspects of the theory. Length is still treated by the learner as a constant, independent of the choice of the frame of reference, and the length contraction is conceived as a distortion of perception. Moreover, since, in the light-clock experiment, the time dilation is explained on the basis of the behaviour of the light, every other problem of time dilation is assumed to depend on the same mechanism, that is, on light.

One point of particular interest for our reasoning is the strategy followed by the interviewer for encouraging the interviewed student to change his metaphysical commitments. The strategy leads indeed to the same results at which almost all the other reviewed papers arrive, in spite of the different routes the authors follow.

The interviewer decided to introduce the orthodox Einsteinian position so as ‘to present the point of view that *events*[1] were more fundamental and that length, for example, could be interpreted in terms of events, that is, something that is localized in space and time’.

This choice led the student to change his focus of attention. While he still believed that there is a reality independent of measurement, he changed his view of how reality manifests itself: it manifests itself by means of events.

The change is explained by arguing that the interviewer used a strategy built according to the model of conceptual change: at first the interviewed student was led to become dissatisfied with his existing knowledge (he was not able to explain time dilation in situations different from the light clock since he was unsuccessfully looking for a mechanism linked to light behaviour), and, then, he was led to deal with an intelligible and plausible new conception (focus on single events), to be reconciled with his old conception of reality so as to evaluate also its fruitfulness.

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[1] Italics is, significantly, in the original text. It is not added.

Other studies, arising out of the so-called misconceptions movement, produced original and thoughtful problems for investigating students' knowledge and arrived at identifying the same kind of difficulties: the tendency for considering the relativistic effects as perspective distortions and the difficulty of giving up the idea of absolute time or absolute simultaneity (Scherr et al. 2001). More specifically the researchers have observed that students often fail to interpret properly the 'time of an event' and the notion of 'reference frame': 'We found that students at all levels tend to treat the time of an event as the time at which a signal from the event is received by an observer. Thus, they consider a reference frame as being location dependent.' (Scherr et al. 2002, p. 1239).[2]

On the basis of these results, Scheer and colleagues produced a curriculum for university students that proved to be successful, being tested by means of a research methodology which employed pretests and posttest with a large sample of students.

Also in this case, the strategy implemented in tutorials is that of focusing on the concept of *event*, following the orthodox Einsteinian view. In particular, two tutorials were designed. The first one aims at guiding students

> to develop the basic procedures that allow an observer to measure *the time of a single distant event*. These procedures form the basis for defining a *reference frame as a system of intelligent observers*. The tutorial then helps students to extend the intuitive notion of whether or not *two local events* are simultaneous by having them develop a definition of simultaneity for events that have a spatial separation. (Scherr et al. 2002, p. 1239, italics added)

The second tutorial aims at guiding students 'to examine the consequences of the invariance of the speed of light through an analysis of the train paradox' (Scherr et al. 2002, p. 1239).

Hence, the tutorials were designed to guide students to the analysis of the Einstein's thought experiments, by a structured and operational concept of frame of reference as a lattice of rules and synchronised clocks or, as Scherr and colleagues say, as 'a system of intelligent observers' (Scherr et al. 2001, 2002). The construction of such a system of intelligent observers implies emphasising (i) the notion of time of a single event, measured by the clock situated in the same spatial position of the event; (ii) the procedure of measuring the time of a distant single event, according to the constraint that there exists a limit to the speed of signals and (iii) the need to generalise the measurement procedure for the time of an event in order to devise an arrangement of observers and equipment that allows the position and time of an arbitrary event to be recorded.

It is curious to note that most secondary and university textbooks teach special relativity following Resnick's approach and, hence, employ presentations similar to Einstein's original 1905 publication. However, unlike Einstein's papers and the original Resnick book, the textbooks pay little attention to what has been proved to

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[2] In a recent survey carried out with about 100 prospective French teachers (de Hosson et al. 2010), a variation of the Scherr and colleagues problem is used in order to identify 'the types of reasoning implemented by prospective physics teachers faced with situations of classical and relativistic kinematics'. Even though the criteria used by the researchers for distinguishing classical and relativistic kinematics seem somehow unconventional, the results confirm what Scherr and colleagues achieved.

be crucial for learning by research in physics education: the role of the concept of event for redefining space and time according to the new constraints of the theory, that is, the unsurpassable and constant speed of light. From an epistemological perspective, despite following Einstein's reasoning, textbooks do not attach relevance to his original operational perspective, which can be seen as consistent with the idea that space and time are special names we give to ways of relating events by measurement (Levrini 2002b).

Because of their empirical orientation, the studies of Scherr and colleagues enlarged the heuristic bases for supporting some results previously obtained by Posner and others. Nevertheless, just because of their empirical orientation, these studies did not enter the debate concerning the model of conceptual change and the robustness of the arguments provided by Posner and colleagues and by Hewson for interpreting the successful results.

These points, instead, were the subject of other works that stressed the need of extending, refining or even revising the model because of the following weaknesses (recognised also by Hewson himself and Thorley, 1989):

(A) The model is not complete, since meaningful learning of the basic concepts of physics would demand not only a deep conceptual change but also a methodological and epistemological change (Gil and Solbes 1993).

(B) The model, in spite of the many attempts to apply it, is far from being a scheme for instruction, since the problem of establishing if and how the conditions required for conceptual change can be realised in classroom (what conceptual ecology) is unsolved (see, e.g. Villani and Arruda 1998).

(C) The framework is essentially epistemological and it does not reflect direct psychological reality. In particular, it 'specifies conditions for change without specifying detailed processes of change' (Levrini and diSessa 2008).

Gil and Solbes (1993), unlike the authors of the other papers discussed below, do not focus their analysis on specific criticalities seen in the model of Posner and colleagues. They simply propose to enlarge it so as to explicitly include the problem of how to promote in students a methodological and epistemological change since, they suppose,

> pupils' difficulties in learning modern physics have an epistemological origin; that is to say, they come from an ignorance of the deep conceptual revolution that the emergence of the new paradigms constitutes. Any meaningful learning of the few elements of modern physics introduced in high school would then be obstructed by the linear, accumulative view presented. In brief: modern physics was *against* the classical paradigm, and its meaningful learning would demand a similar approach. (Gil and Solbes 1993, p. 257)

According to this hypothesis, the researchers designed a programme for high school students where, as far as special relativity is concerned, experiments similar to those of Michelson and Morley were discussed to force the students both to question the existence of absolute space and time and to recognise that, in classical mechanics, there are implicit assumptions, i.e. assumptions that were accepted as obvious, and, because of that, their revision constituted one of the main difficulties in the development of science. By implementing the research methodology of comparing an experimental group and a group of control of high school students, they demonstrated that the teaching programme was effective for enabling students to derive 'quite easily' the variation of space and time. The success is explained by saying that once the relativity of time intervals and lengths for different observers are accepted as hypotheses, learning becomes easier: the programmes of activities 'that aim at producing in pupils a conceptual change similar to the historical change of paradigm' revealed to be effective since they gave 'a more correct view of physics – and particularly of modern physics – with a constructivist approach' (Gil and Solbes 1993, p. 260).

The work of Villani and Arruda (1998) stems from the acknowledgement of a specific criticality in the model of Posner and colleagues: the acceptance of a counterintuitive theory like special relativity is a complex problem underdeveloped in the model of Posner and colleagues. In real situations, instruction seems to be successful, but

> this apparent success can be misleading, since, at this moment in the students' intellectual development, the acceptance of the theory is only provisional, because its plausibility is external to their deep convictions… It would seem that not enough effort has been exerted to render the principles of the theory compatible with students' conceptual ecology. … As a consequence the learning of the Special Theory of Relativity rapidly disintegrates and students remember only a few disconnected elements mixed with many spontaneous ideas about absolute space and time. (Villani and Arruda 1998, p. 88)

The researchers argue that, in order to increase intelligibility and to transform a superficial sense of plausibility into a stronger one (so as to give stability to knowledge), the minimal conceptual ecology should include the troubled story that special relativity had to go along for being *accepted* by the scientific community. The argument of the analogy between historical ideas and some of the tendencies in spontaneous reasoning is developed, in this case, by focusing on a specific moment of the history of special relativity: the moment in which Einstein realised that

> he was unable to produce a microscopic model of the interaction between matter and radiation, so he decided instead to formulate a theory based on two universal principles. He used an analogy with thermodynamics, in which the principles and consequences are derived from the impossibility of perpetual motion, without any components of matter. (Villani and Arruda 1998, p. 91)

The Einsteinian distinction between theories of principles and constructive theories (Einstein 1919) is considered to be a profound epistemological and ontological change in the debate about the acceptance of the consequences of the Lorentz transformations (i.e. the relativistic effects)[3]: debate dominated, until that moment, by the theory of the electron of Lorentz, according to which length contraction, for example, had to be understood by searching for a microscopic mechanism. This profound change was, according to the study by Villani and Arruda, one of the main reasons of the difficulties the theory met to be accepted.

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[3] The role of thermodynamics in the genesis of SR is extensively argued in the paper of Abiko (2005) which will be discussed later.

In spite of the interesting example of historical reconstruction carried out from an educational perspective and in spite of the relevant focus of the research (the problem of acceptance), the authors are very prudent in their conclusions:

> We do not expect students to go through a conceptual change in the sense of systematic change in the way they analyze physical phenomena: we only hope that they will become aware of the existence and the essential features of a conceptual change in the history of science and that they will realize that this change allowed modern technology to advance. (Villani and Arruda 1998, p. 94)

The problem of entering the cognitive mechanism for a deep acceptance remains theoretically unsolved.

The paper of Levrini and diSessa aims at entering more deeply the cognitive process of change in learning special relativity, by applying a carefully defined and tested theory: ‘coordination class theory’ (diSessa and Sherin 1998).

Coordination class theory is a developing model of concepts and conceptual change, framed in a ‘complex knowledge system’ perspective and consistent with the epistemological perspective of ‘knowledge in pieces’ (diSessa 1993). In this view, a ‘concept’ is not seen as a single, unified idea but a large and intricately organised system, which effectively coordinates activation and use of many specific elements according to context. Learning a concept is seen as a process of recruiting and ‘coordinating a large number of elements in many ways’. According to such a theory, empirically tracking those different ways to achieve the effect of a concept leads to better understanding of learning and failing to learn.

The type of cognitive process analysis carried out in the study of Levrini and diSessa is based on the following assumptions:

(a) Using a carefully defined and tested theory or model allows a more precise tracking of data, in order to see in more detail *when* various kinds of learning events are happening, *what* their nature and effects are, and *why* they happen.
(b) As a result, data can overturn or improve even insightful, but rough, guesses as to the source of learning difficulties and how to overcome them.
(c) Well-developed (learning) theory, as in physics, applies to a broader range of situations than those out of which it arose. Insights from one context can be bootstrapped more reliably into broader insights concerning learning physics.

Specifically, the paper contains an analysis of a single classroom episode in which secondary students reveal difficulties with the concept of proper time but slowly make progress in improving their understanding. The concept of proper time, like the concepts of proper length and mass, is particularly tricky since its understanding is strongly dependent on the level of appropriation of the shift from a Newtonian space plus time to the relativistic space-time. Its property of invariance, as effectively stressed in the book of Taylor and Wheeler, is indeed an expression of the invariance of space-time interval between two events.[4]

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[4] Also the invariance of mass is strictly related to the relativistic space-time structure, being the module of energy- momentum 4-vector. This point is addressed very effectively by Taylor and Wheeler, and it would be worth understanding why many textbooks and teachers still use the

The concept of proper time is usually introduced, in teaching, through the light-clock thought experiment. But the analysis and discussion of this thought experiment do not usually focus on *those specific* space-time properties of *those couple of events* whose space-time interval is called proper time (e.g. by defining proper time as the time interval measured by *two events occurring in the same position*). The light-clock thought experiment is instead used for defining proper time as the *time duration of a phenomenon* (the back and forth travelling of light ray) measured in the frame of reference *at rest with respect to* the light clock. A good guess, supported also by the works of Hewson mentioned above, is that students expect, in every other context where proper time has to be determined, simply to see an object (like the light clock) that determines the relevant frame, or, slightly more complexly, the frame is determined by the (potentially moving) 'location of the phenomenon' whose duration is to be measured. This implies that teaching may reinforce the persistence of 'classical ontological inferences' that take for granted the existence of phenomena as unproblematic things that have a place and a duration. This is what happened in the classroom episode analysed in the paper of Levrini and diSessa, where it is shown, by applying the coordination class theory, that the students tend to maintain a classical ontology which led them to *coordinate* the property of invariance as an inner, intrinsic, property of a phenomenon.

The paper argues, like other papers mentioned above, that changing students' perspectives from 'looking in terms of phenomena' to 'looking in terms of events' is an educational goal that, if accomplished, substantially promotes effective conceptual competence. In the context of the coordination class theory, the shift in the fundamental view of the universe, from a place in which there are objects and phenomena to the universe as an ensemble of events, is explained as that cognitive process which implies:

(a) Identifying the space-time events as preferred foci of attention for all relevant determinations, that is, for preferentially using a particular class of strategies for *reading out*[5] information from a context (e.g. reading out from the context *what events* are of interest) and for *inferring*, from the readouts, the particular information at issue (e.g. *how* the events are related with one other in space-time)

(b) *Displacing* persistent ontological assumptions about length and duration of things and phenomena (objects and phenomena relate to space-time measurements only and precisely for the family of events that the object/phenomenon 'lays down' in space-time)

(c) Factoring the space of possible *concept projections of all coordinations* in special relativity (the particular knowledge used in applying a concept in different situations)

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notion of relativistic mass (a mass dependent of velocity), in spite of the sharp criticisms known in literature (e.g. Adler 1987; Warren 1976; Whitaker 1976).

[5] The words in italics are technical words within the coordination class model. Their detailed explanation is beyond the scope of the paper. They are extensively described in the paper I am reviewing (Levrini and diSessa 2008).

As far as the last point is concerned, possible projections of coordination, enacted by students and/or suggested by some definitions in special relativity, are, for example, (i) first identify the set of relevant events and then proceed from there (determining other things on the basis of properties of the relevant events), (ii) 'finding the *right* frame of reference to make our coordination – our way of determining the relevant quantity – easier' and (iii) 'sitting on the relevant object or phenomenon'. Factoring, as it is shown in the paper, includes giving priority, over the other possible classes, to the class of projections that first identify the set of relevant events: all the other possible classes are proved to have little span (they work only in particular cases) and/or reinforce the persistence of classical ontological inferences.

The detailed analysis allowed the authors to put forward implications on teaching and on investigations about the role of history and epistemology of physics in teaching/learning special relativity. In particular, the application of the coordination class model to the data provided a theory-based explanation of *why* explicitly exposing, managing and relating multiple classes of projections of a physical concept seem to be a good instructional technique to work around documented difficulties in conceptual change in special relativity. Indeed, the positive reaction of the students facing their difficulties can be ascribable also to the fact that they were previously guided to compare the operational and geometrical approach to special relativity, by analysing excerpts of the original publications of Einstein and Minkowski. The comparison between two different approaches was chosen by the teacher as a way to bring the complexities of historically different interpretative perspectives into the classroom and to situate special relativity within the philosophical debate about space and time. Before the analysis, the richness and diversity of the thinking about the historical context was the 'secret ingredient' in achieving greater conceptual competence. The analysis, instead, led the researchers to believe that a coordination class perspective explains some of that success: framing multiple classes of projections as historical perspectives stimulated students to confront *consciously* the two main sources of learning difficulties that the coordination class model hypothesises – the problems of *span* and *alignment*. *Span* concerns the problem of having adequate conceptual resources to operate the concept across a wide range of contexts in which it is applicable, while *alignment* concerns the problem of being able to determine the same concept-characteristic information across diverse circumstances.

To sum up, the overview of the papers about teaching/learning special relativity framed within the conceptual change strand shows a significant variety of research methods and arguments progressively developed within PER for diagnosing students' difficulties, pointing out critical aspects of traditional curricula, explaining successes and failures and providing suggestions for innovative and effective instruction.

The most important point I want to stress here is that significant studies, carried out by applying different research methodologies according to different theoretical perspectives, provide multiple cross arguments for supporting one common point: guiding students to look in terms of events is crucial for promoting deep understanding in special relativity. This point has been shown to be a critical detail (Viennot et al. 2005), i.e. a *detail* whose disregarding can prevent students from grasp the *global meaning of the theory*. Within the forest of results obtained by PER and the jungle of methodological procedures invented and/or applied, the agreement on this result, as well as the quality of the process followed for achieving it, should elevate it to a robust piece of knowledge which every new teaching proposal should rigorously assume as a constraint. This case is an effective example for showing that PER is established as a research field which is able to obtain shared results and to claim 'this is where we are', as far as the research on students' difficulties in special relativity is concerned.

In the papers considered in this section, the relevance of specific aspects of history and philosophy of physics (the reference to the orthodox original interpretation of Einstein, the troubled story of its acceptance and the comparison between different perspectives, such as those of Einstein and the Minkowski) was supported and argued on the basis of epistemological or cognitive arguments stemming from the problem of how conceptual change can be studied and promoted.

The design of a teaching proposal or a teaching approach is, however, a process that usually aims at going, if possible, beyond its effectiveness in structuring a conceptual landscape suitable for supporting conceptual change and deep understanding. A teaching proposal or an approach is a complex cultural construction that an author or a team of authors produce for promoting also a specific view of physics and of learning and/or for exploiting the role of science education in the intellectual and emotional growth of pupils. In the next section, the debate about the role of history and philosophy of physics is addressed within such a strand, that is, within the general problem of how to promote physics as culture.

6.4 The Debate About the Role of History and Philosophy of Physics for Promoting Physics as Culture

Besides Resnick's and Taylor and Wheeler's teaching proposals, there have been other important projects.[6] In the set of proposals, some of them[7] represent historical reconstructions inspired either by an experimental approach built on the limiting value of the speed of light and, consistently, on Bertozzi's experiment realised within the PSSC project (Cortini et al. 1977; Cortini 1978) or by Taylor and Wheeler's approach (Borghi et al. 1993; Fabri 2005).

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[6] See, for example, Arriassecq and Greca (2010), Borghi et al. (1993), Cortini et al. (1977), Cortini (1978), Fabri (2005), Levrini (2002a, b), Solbes (1986), and Villani and Arruda (1998) for secondary school students and Angotti et al. (1978), Scherr et al. (2002) for university students. The list is certainly incomplete. I am quoting only the proposals I found cited in the research literature. Yet, in some cases, I did not have direct access to the whole texts because they are teaching texts and, hence, written only in the national language.

[7] See Borghi et al. (1993), Cortini et al. (1977), Cortini (1978), and Fabri (2005).

Other proposals refer explicitly to the need of a historical-philosophical contextualisation of teaching for stressing the cultural value of special relativity.[8] All these proposals share the aim of addressing history in a way so as to overcome the teaching habits of referring to a fictional pseudo-history, focused on an over-evaluation of the Michelson and Morley experiment, that many textbooks disseminate and that tends to promote a hyper-simplified and unrealistic form of empiricism (Holton 1973). They moreover share the belief that a historical contextualisation is needed to achieve a high educational goal: to stress and to exploit the philosophical implications of a theory which led explanatory paradigms to be changed and/or which had an impressive influence on other cultural fields such the arts, literature and music.

The implementations of these proposals, usually carried out by the researchers themselves who designed the proposal or under their supervision, obtained results that are said to be encouraging and efficient. In particular the authors seem to agree that their results show that even secondary students manifested great interest in the matter and made no complaints about the mathematical complexities involved. As I discussed in the previous section, some of these proposals evaluated their effectiveness by framing students' reactions within the conceptual change strand.[9]

Even though their effectiveness was tested according to conceptual change models, the proposals of Gil and Solbes (1993) and Levrini (2002b) were however designed within a research strand which received greater and greater attention during the 1990s: the problem of what image of physics should be promoted in teaching (Grimellini Tomasini and Levrini 2001). For example, Gil and Solbes claim:

> High school teachers and textbooks transmit an incorrect image of science, which ignores the existence of crises and paradigm shifts. The introduction of topics of modern physics, in particular, takes place without reference to its essential novelty or to the main differences between the classical and the new paradigm. A suitable occasion for showing the richness of the development of science and importance of science revolutions is thus wasted. (Gil and Solbes 1993, p. 260)

The issue of the image of science triggered a deep debate about the problem of the relationship among history of science, philosophy and science education.[10] The debate led to a new research field, history and philosophy of science and science teaching (HPS&ST), to be progressively established, but, as pointed out by Galili in a recent paper, 'despite the intensive support for using the HPS in science teaching and articulation of its advantages (e.g., Matthews 1994, p. 38), the issue continues to be complex and controversial' (Galili 2011).

In the specific research literature of HPS&ST, original contributions about teaching/learning relativity, provided either by professional historians or philosophers to science education or by science education researchers deeply

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[8] See Arriassecq and Greca (2010), Levrini (2002a, b), Solbes (1986), and Villani and Arruda (1998).

[9] See Gil and Solbes (1993), Levrini and diSessa (2008), Scherr et al. (2001, 2002), and Villani and Arruda (1998).

[10] See, for example, Bevilacqua et al. (2001), Cobern (2000), Duschl (1985), Gauld (1991), and Matthews (1994).

involved in historical-philosophical studies, are curiously rather few. Nevertheless, they can be significantly compared for discussing the role that a specific research in history and philosophy of special relativity can play in designing teaching proposals.

Levrini, in her works (2000, 2002a, b, 2004), presents an educational reconstruction of the influence of historical-philosophical debate between 'relationalism and substantivalism' on the concepts of space and time in physics. In particular, the original publications of Einstein, Minkowski and Poincaré were comparatively analysed in order to trace back the historical-philosophical roots of the interpretations of general relativity inspired, respectively, by the works of Sciama, Wheeler and Weinberg. The educational reconstruction was motivated by a specific cultural and educational assumption: 'teaching relativity at the secondary school level gains particular meaning if the theory is critically situated within the cultural debate on space and time and if the role of history and philosophy of physics is exploited in order to *provide students with keys for comparing different interpretations of the theory*'. (Levrini 2004, p. 621, italics added). Historical and philosophical debates are assumed, if they are properly reconstructed from an educational point of view, to be an effective teaching strategy for helping 'students to focus on the peculiar aspects of each interpretation and to elaborate logical, cultural, rhetorical, cognitive instruments for comparing different perspectives and for expressing their own preferences' (Levrini 2002b, p. 613).

Another historical debate which has been subject of many controversies among the historians of physics concerns the genesis of special relativity and, in particular, 'the so-called Lorentz-Einstein problem,' i.e. the question of whether or not Lorentz and Poincaré built, slightly before Albert Einstein, the special theory of relativity. The issue, like every historical issue about the paternity of ideas, triggered heated debates among historians.[11] Nevertheless, within secondary school textbooks or in science education literature, the discussion on the genesis of special relativity is still strongly focused on the figure of Einstein and on the role played by the Michelson and Morley experiment. In other words, the debate on the genesis of special relativity, when it is mentioned or discussed in textbooks or in research papers which report teaching proposals (e.g. Arriassecq and Greca 2010), seems to refer more or less explicitly to the perspectives of Holton (1973) and Resnick (1968).

In the specialised and recent literature of HPS&ST, two historians of physics addressed the issue of the genesis of special relativity from an educational perspective, Abiko (2005) and Giannetto (2009). The two papers focus on different aspects on the issue and support different theses.

Abiko addresses his historical reconstruction of the genesis of special relativity by tracing the origins of Einstein's view back to thermodynamics. In the paper, the

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[11] Within this debate, very strong positions can be also found for supporting the role played by Poincaré (see, e.g. Bjerknes C. J. (2002), *Albert Einstein, The Incorrigible Plagiarist*, XTX Inc, Downers Grove, Illinois ; Hladik J. (2004). *Comment le jeune et ambitieux Einstein s'est appoprié la Relativité restreinte de Poincaré,* Ellipses Édition Markenting S.A, Paris; Leveugle J. (2004). *La Relativité, Poincaré et Enstein, Planck, Hilbert. Histoire véridique de la Théorie de la Relativité*, L' Harmattan, Paris).

crucial point of departure for Einstein is said to be ‘his encounter with Planck’s derivation of the radiation-formula…, and [his] resultant distrust of contemporary electromagnetic theory’. On the basis of a new analysis of Einstein’s *Autobiographical Notes*, Abiko arrives at arguing that “Notes’ make clear that, of the three theories of classical physics (i.e., mechanics, electromagnetic theory, thermodynamics), Einstein regarded thermodynamics as the only physical theory of universal content that will never be overthrown within its sphere of applicability’ (Abiko 2005, p. 359). According to his thesis, Abiko sees ‘an obvious and crucial discrimination between Lorentz-Poincaré’s theory and Einstein’s STR [which] rests on the difference between the constancy of light-velocity and the light-velocity postulate. Both Lorentz-Poincaré and Einstein believed in the constancy of light-velocity. But, it was Einstein and only he that elevated it to the status of the postulate’ (Abiko 2005, p. 353). The reason of that is, again, Einstein’s distrust of Maxwell’s electromagnetism: ‘in order to transcend Maxwell’s electrodynamics, he had no choice but to elevate the constancy of light-velocity deduced from the latter to the status of the light-velocity postulate’ (Abiko 2005, p. 357).

In his paper, Giannetto (2009) supports the thesis that ‘[t]he revolution in XX century physics, induced by relativity theories, had its roots within the electromagnetic conception of Nature. […] The electromagnetic conception of Nature was in some way realized by the relativistic dynamics of Poincaré of 1905. Einstein, on the contrary, after some years, linked relativistic dynamics to a semi-mechanist conception of Nature’. (2009, p. 765). By semi-mechanistic he means that ‘in Einstein there is a residual form of a mechanist conception: mechanics is always considered the first physical science and constitutes the independent foundation of all physics’ (2009, p. 774).

Independently of the supported theses, the two papers seem to share a similar view about the educational and cultural relevance of a historical approach focused on the genesis of special relativity, i.e. on that process of a new theory’s emergence and acceptance. They both stress, in particular, the importance of enabling students to enter twentieth-century physics as ‘the transition from the ‘clockwork mechanism’ of Newtonian science to the ‘evolutionary process’ of modern science’ (Abiko 2005, p. 362) or to ‘a ‘new alliance’ (Prigogine and Stengers 1979) among God, mankind and nature, a new cosmic and ethic order, not pre-fixed but the fruit of a complex dynamical, temporal free evolution’ (Giannetto 2009; p. 778).

The two papers, moreover, share the emphasis on the relationship to other scientific theories, worldviews and surrounding social and cultural factors:

> beyond the general non-dogmatic method of science research, science has no unique worldview. Science in its historical practices is the place where different worldviews [like Mechanist, Thermodynamic; Electromagnetic] have been in conflict with each other. Not only different scientific theories, but even different formulations of a scientific theory have different presuppositions and implications for worldview as well as for religion. (Giannetto 2009, p. 779)

The last quotation touches a very delicate point – somehow dramatic – that researchers in science education have to address when they want to design a teaching proposal: To what extent am I imposing my personal worldview in the design of a teaching proposal? What ideological reasons am I projecting into the proposal? If the proposal is based on a historical/epistemological approach, what historical-philosophical interpretation of a theory should I choose? Why? Why should my personal worldview have a higher educational value than another?

In the light of questions like these, history and philosophy/epistemology can play a crucial role: 'Especially within an educational framework, one should never impose her/his private worldview *but one should deal with the science/religion problem from a historical perspective: one should show how science practices involve a conflict among various worldviews'* (Giannetto 2009, p. 766, italics added).

The focus of the papers of Levrini, Abiko and Giannetto on fundamental debates (the debate between 'substantivalism and relationalism' and the debate about the genesis of special relativity) highlights a relevant role for history and philosophy: they provide some examples for showing how history can allow different philosophical/epistemological interpretations and different worldviews to be *analysed in perspective*, that is, comparatively analysed not as 'orthodox or heterodox' positions but as different possible perspectives from which a theory can be seen.

The overview of the research work about the design of teaching proposals allows me to conclude that:

- There exist few attempts at designing new teaching proposals about special relativity; most of the work is still strongly influenced by the two main approaches of Resnick and Taylor and Wheeler.
- The proposals are usually presented and supported within physics education research in terms of their effectiveness in motivating students or in triggering processes of conceptual change.
- The debate about the cultural and philosophical/epistemological presuppositions that exist behind an interpretative choice concerning special relativity presentation is undeveloped, but it would be fundamental for comparing different proposals.
- In order to foster comparability, history can play the specific and significant role of allowing different philosophical/epistemological interpretations of a theory to be *analysed in perspective*; it can allow the different nuances of the proposals to be explored as expressions of different worldviews rather than to be *classified* in terms of 'orthodox/heterodox', 'better/worse', 'closer to/further from the historical truth'.

The choice of presenting special relativity from different perspectives is not only cultural and ethical: as shown in the previous section, it can have important implications for learning (Levrini and diSessa 2008), and, as I will show in the next section, it is fundamental for teacher education (De Ambrosis and Levrini 2010).

6.5 Teacher Education

As well as the cultural value of the proposals and their effectiveness, demonstrated in implementations carried out under the supervision of researchers who designed the proposals, another issue, fundamental for improving the teaching/learning of special relativity and for filling the gap between research and school reality, is how to enable teachers to manage and implement autonomously innovative, effective and culturally meaningful teaching proposals (Grimellini Tomasini and Levrini 2001, 2004).

The general research issue of how to promote innovation in school through teacher education has been the object of many studies, since 1990. For example, the STTIS (Science Teacher Training in an Information Society) European Project (1997–2001), aimed at identifying and analysing transformations between what was expected by implementing a research-based sequence and what is observed when teachers put innovation into practice, produced very important research results on this issue. In particular it showed that implementation often implies a transformation of the original proposals, sometimes with the loss of important aspects of innovation (Pintò 2005).

The studies in this research strand pointed out some general tendencies or common attitudes of teachers toward approaches they perceived as innovative:

- The tendency of accepting or refusing the whole proposal on the basis of personal or local criteria and the difficulty in moving from a global scale to a local one (in recognising the 'critical details' of a proposal): 'Critical details are not always disregarded by teachers because their grasp of the global rationale is superficial. It may result from a lack of training as to a connection between details and global rationale' (Viennot et al. 2005)
- The tendency of mixing new with the old (Viennot et al. 2005) and of transforming the proposal so as to obtain intellectual and professional satisfaction
- The tendency of accepting the challenge of going deep into the proposal only if it represents an answer to disciplinary problems recognised as crucial by the teachers (Eylon and Bagno 2006)

Within this research strand, a specific project was carried out for analysing teachers' attitudes toward Taylor and Wheeler's (TW) proposal (De Ambrosis and Levrini 2010). In particular, the paper concerns an empirical study carried out with a group of 20 high school physics teachers engaged in an *at-distance* (based on a e-learning platform) masters course on the teaching of modern physics. The data refers to the module on special relativity, of which the authors of the paper were the trainers. The focus of the study was the process through which teachers analysed the TW textbook in order to appropriate it for the perspective of designing their own paths for use in the classroom.

The results obtained in the study allowed the researchers to argue that problems known in the research literature and usually related to the implementation process can already be found when teachers approach the proposal and try to appropriate it. The article demonstrates that by focusing on the appropriation process, it becomes possible to provide arguments to support that while the first tendency (being trapped in a local vision) represents a real obstacle for innovation, the last two tendencies can be transformed into productive resources, if 'properly' (at suitable *moments* and in appropriate *ways*) activated.

The paper of De Ambrosis and Levrini is here presented and discussed to stress its contribution in pointing out indications that teachers' reactions can provide to research for designing innovative curricula, as well as further nuances of the role that history and philosophy of relativity can play in teaching/learning special relativity.

In the study, the appropriation process, followed by the group of teachers, was reconstructed in terms of stages and factors triggering the progressive development of teachers' attitudes and competences, as briefly presented below.

In particular, three stages were identified:

(A) *The acceptance of the game,* from the initial 'distrust' toward the proposal's novelties to the point of seeing the proposal as authoritative (a worthwhile, although demanding proposal)

(B) *The game,* played by going on, with patience and determination, in the analysis up to the critical point where it is possible not only to discover the details but also to attain a global perspective on the proposal

(C) *The exploration of the offstage of the game,* carried out in order to acquire criteria to make the proposal explicitly 'comparable' with proposals more familiar to the teachers (that of Resnick)

The authors of the paper argue that the first stage in the reaction of the teachers in face of the Taylor and Wheeler proposal was of distrust and resistance:

- The attention of the teachers was focused on very specific points of the proposal.
- They manifested the willingness of proposing immediately new alternatives (*it is better to start from a real problem, for example, from Michelson-Morley experiment).*
- The teachers referred to 'students' and 'personal experience' as arguments for distinguishing 'what works and what does not work': (*I think that a lot of confusion can be generated, in particular, among the less motivated students*).

The most important point, stressed in the paper about this phase, is that the attitude changed as soon as the discussion moved to disciplinary concepts that sounded puzzling for the teachers, like the definition of inertial systems and the relation between the inertial systems in Newton's mechanics and the free-floating inertial systems introduced by TW.

Through disciplinary puzzling points, the teachers arrived, after the analysis of the first two chapters of the book, at the shared conviction that to examine the proposal in depth is worthwhile: local elements belonging to the plan of teachers' disciplinary content knowledge proved to be crucial for triggering a more general change in the teaching perspective. The teachers indeed not only recognised some weaknesses in their disciplinary knowledge, but the kind of problems led them to acknowledge that local disciplinary inconsistencies in traditional teaching cannot be always solved by local interventions: they require sometimes a wider reconstruction or even a change of perspective.

This evidence is worth being stressed, since it confirms a result previously achieved also by Eylon and Bagno (2006): the authoritativeness of a proposal is evaluated by the teachers, first of all, in terms of its effectiveness in solving *specific disciplinary* problems *they* feel *real*.

The second stage described in the paper lasted from the analysis of chapter 3 to the end of TW book. During this phase the teachers moved from the search for answers to puzzling conceptual problems to the critical point where it was possible not only to discover the details but also to attain a global perspective on the proposal.

This stage is described by stressing how it was characterised by a special attitude (very different form the initial one): teachers showed they can be collectively involved in a medium term, patient and resolute search for shared *global criteria* of analysis and, in particular, in the problematic search for the *coherence* of this unusual proposal.

In the group, a stimulating discussion about coherence represented an important moment since the teachers could express and compare many different positions existing among them:

- Coherence as *logical development of a path from classical to modern physics*, as a result of a radical reconstruction process of the physics contents
- Coherence as *historical development* of a path
- Coherence as *systematic use of the experimental method* characteristic of physics inquiry
- Coherence as reconstruction of the physics contents starting from *fundamental concepts and categories such as the space-time description, causality and determinism*

The discovery of such a plurality of positions is argued to have been an important moment for orienting the collective investigation toward the acknowledgment of that special kind of coherence that characterises TW's approach. The teachers indeed arrived at accepting as sensible criteria for coherence some choices that are at the basis of the TW approach and that the teachers could deeply appreciate only at the end of the analysis: the choice of reconstructing special relativity in the light of general relativity and the choice of consistently revising all the concepts in the frame of a geometrical 4-dimensions space-time.

In the group it became clear that, as one teacher wrote,

> in order to grasp the coherence of an approach it is necessary to internalize the meaning of a theory far beyond its formal aspects. It implies to go deep, to analyze its implications, to acquire different perspectives and interpretations. It means to know both the origin of the hypotheses and their consequences. The task is not easy for a teacher.

In the paper, it is shown how, at the end of the analysis, there was a general sense of satisfaction, a general agreement on the relevance of the proposal.

The authors of the paper argue that two factors have probably triggered or supported the process in the second step:

(a) The presence, within the group, of lively dynamics able to support the maturation of a shared conviction that global evaluation criteria were needed for justifying local choices.

(b) The strong inner coherence of the textbook that enabled the trainers to firmly support the awareness that specific physical problems, addressed by this proposal and not solved clearly in a traditional approach, could not be always solved by local changes.

At the end of the collective analysis of the book, everything seemed in order. The proposal was recognised and accepted as authoritative, intelligible, innovative, culturally relevant and intellectually stimulating. But some final comments revealed a new form of distrust: the criteria for coherence were too subjective. I report here two comments of the teachers since they represent the basis for discussing, in the following, the specific role played by history and philosophy in this study:

> The proposal appears somehow as unilateral. … I feel however a kind of mistrust (perhaps only intuitive) toward the question. As we were in front of a sort of situation forced by [the need of] searching for an excessive intelligibility in the relations between the physical quantities (Mario).
>
> I would like to focus on the hypotheses at the basis of TW's approach: I feel that there are non-explicit hypotheses or that I got lost along the path… I would like to improve my understanding of the whole proposal and be able to compare it with others around (Anna).

Teachers' comments showed that the process of appropriation was not complete: understanding the content is necessary but not sufficient to grasp the general meaning of a proposal and to feel comfortable with it; further tools were needed for disassembling and reassembling it, for going deep into its epistemological and cognitive assumptions (to what image of physics and physics teaching it is related), for comparing it with others (especially the typical textbook ones) and for adapting it to one's teaching/learning attitudes and constraints. Teachers' comments pointed out that the tricky 'problem of comparability' had to be collectively addressed.

During the third stage, the teachers were guided to critically analyse TW's approach in comparison to Resnick's. In order to make the two proposals comparable, the trainers used the teaching strategy of supporting the teachers in reconstructing the historical and philosophical roots of the two teaching proposals. In particular the teachers were guided in the analysis of the original publications of Einstein (1905) and Minkowski (1909) in order to find the historical roots of, respectively, Resnick's and TW's approach. The trainers gave the teachers materials prepared by the researchers of the group in Bologna that framed the original publications within the historical and philosophical debate on the concepts of space and time in physics: from Newton's *Principia* and the criticism by Leibniz and Mach, to general relativity, passing through Einstein's, Poincaré's and Minkowski's works and worldviews.

The main surprise for all the participants was the tone of the discussion, which showed that the teachers were, consciously but prudently, moving from the need of searching for the implicit assumptions of the TW textbook to the critical point where it was possible to compare the two approaches as different choices of content reconstruction inspired by different global views of the theory and of its teaching. As a teacher wrote, 'I was surprised by the "harmony" of the discussion on epistemological issues. Generally these discussions reveal very rigid points of view and irreducible convictions'.

The factors triggering the process of going beyond an ideological clash were probably some features of the materials, which encouraged the teachers to trace back the historical roots of the proposals and to situate such roots within a philosophical debate. In this case, the historical-philosophical dimension allowed the reconstruction of the interpretative dimension of each proposal, and this dimension was seen to be effective for making them 'commensurable'.

The reconstructed moving picture of the appropriation path showed that a multifaceted and complex 'process of change' is implied: appropriation requires teachers to become able to master the overall proposal at different levels (details, rationale and implicit presuppositions) and to coordinate different dimensions of knowledge (disciplinary, cognitive, philosophical and educational).

The study points out relevant indications for the design and the production of materials for teacher education. In order to foster appropriation, (i) the materials have to be built on a disciplinary reconstruction effective for solving conceptual problems that teachers feel relevant; (ii) they must show a strong local–global consistency (from details to rationale); (iii) they must be proved to be effectively usable in class; and (iv) they must be comparable with what teachers feel closer to, as well as suitable to be disassembled and reassembled according to different personal teaching styles, images of physics and of teaching. The last point implies that the presuppositions of a teaching proposal must be made explicit: for that purpose, the studies developed so far on teaching/learning special relativity revealed that a historical and philosophical/epistemological approach can be useful.

In the paper of De Ambrosis and Levrini, it is however argued that these features of materials are fundamental for appropriation mainly because they enabled the trainers to enact particular training strategies.

Just to give one example, in the paper, it is described how trainers acted in order to manage the lively and messy forum on Chapter 1 – where Taylor and Wheeler give an overview of the entire proposal. Instead of giving in to the temptation of providing quick – and necessarily partial – answers, the trainers prepared a document where the main problems and conflicting points arisen in the discussion were reported. The document was shaped as a sort of agenda of the whole course, indicating where the questions would have found, in their opinion, their 'natural' moment for discussion. In more detail, the trainers proposed an agenda where the trainers differed: problems concerning conceptual difficulties well known in the research literature (to be discussed in short-medium terms during the scheduled activity devoted to the analysis of specific research articles), perplexities concerning basic choices of the proposal (to be discussed in medium-long term and, in particular, at the end of the analysis of the whole textbook and during the analysis of the original works of Einstein and Minkowski) and problems concerning the implementation in class (to be discussed in long term).

The choice was made initially as a survival strategy in the face of the avalanche of questions to which the trainers could not practically respond because of the time and means imposed by the web communication. At the end the choice was revealed to be effective for changing the general attitude of the teachers' group and of the trainers themselves: the web communication and the necessity of communicating through written texts allowed all of them to keep track of the problems and of the whole process.

This awareness contributed to overcoming the attitude of ‘all-now-fast-and-easy’ and to create a more relaxed atmosphere where different learning rhythms could have room. Moreover it contributed to giving a strong and coherent signal that an appropriation process is long, complex and multidimensional.

This study showed how the materials themselves, because of their specific features, acted as the basis for mediating the relationship between teachers and trainers: their being intellectually stimulating, locally-globally coherent and explicit enough in their presuppositions to be comparable with the more familiar proposals allowed the trainers to play the role of creating that *space of analysis and discussion* where each of the participants could follow her/his learning pace, explore her/his point of view, and take care of and the accountability of her/his appropriation path.

The example, however, points out a tricky problem: teachers’ appropriation cannot be simply analysed in terms of a relation between teachers and teaching materials. Teachers’ appropriation of new teaching materials is a complex and delicate process involving a relationship between teachers, teaching materials, proposals’ designers and trainers. This relationship is complex and delicate for at least the following reasons:

- Teachers, designers and trainers are professionals with interwoven but distinct and differing competences; the relationship implies different roles to be acknowledged and exploited.
- The relationship is strongly influenced by the features of the materials; trivially, if the materials are shaped as closed packages of activities designed by researchers to be followed step by step by teachers, they induce, implicitly and explicitly, a deeply different relationship between designers, trainers and teachers with respect to materials shaped as a ‘properly complex territory’ (Bertozzi et al. in press; Levrini et al. 2010, 2011; Levrini and Fantini 2013) where different approaches and different learning routes are comparatively discussed.

To conclude, the studies carried out about teacher education in special relativity point out a delicate research issue which would deserve a special attention in the coming years. The issue concerns the relationship between research products, teachers, designers and trainers that is, more or less explicitly, mediated by the *structure*, the *format* and the *features* of the produced teaching materials. Structure, format and features of the materials are, indeed, carriers of that image of physics and of teaching on which the relationship between proposals’ designers, trainers and teachers is established and on which the different roles can be played.

6.6 Conclusion

The paper provides a review of the main studies concerning teaching/learning special relativity. The review has been carried out with the following goals in mind:

- To identify the many dimensions (research strands) on which the problem of improving teaching/learning of special relativity has been so far projected in order to be studied. The resulting survey of the literature presents the image that all of the dimensions are intimately related and, given the inner complexity of every process of teaching/learning, they all must be considered in a meaningful educational reconstruction of relativity: 'to change one variable at a time [e.g.: introducing new problems, a new experiment or the analysis of an historical episode] simply doesn't work' (Duit 2006).

- To present, within each strand, what results can be considered stable and/or most current, including what problems are still unsolved.
- To stress the multifaceted role ascribed to history and philosophy of physics in the specific research domain which concerns teaching/learning special relativity.

The overview revealed that the research strand concerning students' difficulties in learning special relativity is well developed and shared results have been achieved. Within this strand, physics education research can be recognised as a developing research field that has produced, over the years, arguments for considering what is scientifically acceptable and what is unacceptable.

Deep unsolved research problems, instead, concern the design of teaching materials and the dissemination of good practices through teacher education.

As far as the first point is concerned, new collaborations between science educators, historians and philosophers of physics would be very useful both for making the historical and epistemological roots of teaching proposals increasingly explicit and for triggering a debate about the comparability of the proposals.

As far as the second point is concerned, further studies seem to be needed in order to investigate the relationship among proposals' designers, trainers, teachers and materials so as to point out new design criteria able to foster authentic and collaborative relationships between the research world and the school world.

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Chapter 7
Meeting the Challenge: Quantum Physics in Introductory Physics Courses

Ileana M. Greca and Olival Freire Jr.

7.1 Introduction

In the last two decades, interest in introducing quantum physics into introductory physics courses at university and high school level as well as research into the subject has increased. New textbooks have been published introducing updated views for undergraduates. There is now wide recognition of how ubiquitous quantum physics has become in current technologies and how fundamental it is considered for physics and for the culture of science. However, as difficulties related to teaching this physical theory in advanced courses are legendary, it comes as no surprise that the obstacles to teaching it in introductory physics courses are much greater.

Presenting quantum theory (hereafter QT)[1] is a task which is both technically and philosophically sensitive. In QT philosophical issues concern the interpretation of its mathematical formalism as well as its conceptual foundations. However, most of the research in science education and instructional materials do not take into account the philosophical choices behind the subject, and some of their results may be biased by the lack of attention to these choices. For instance, the right answers to questions related to wave-particle duality are not independent of interpretational choices, and it is even difficult to find consensus among experts as to such answers.

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[1] Physicists interchangeably use quantum theory, quantum physics, quantum mechanics, or wave mechanics to describe the same physical theory. While using sometimes quantum physics, we will privilege quantum theory as it emphasizes its role as a scientific theory given that theories are central to the culture of physics.

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As regards research on the conceptual foundations of QT, this investigation was not over at the time of its inception. Indeed, we now have a better understanding about what quantum physics is from the ongoing controversy on its interpretation and foundations. The statement that QT does not fit the usually accepted local realism requirements, for instance, is a consequence of Bell's theorem and its experimental tests. This is a chapter in physics whose history was renewed in the 1960s and has since continued to evolve. The history of this foundational research seems to lead to two different and to some extent conflicting conclusions, both with implications for the business of physics teaching. The first says that quantum physical concepts have no classical or intuitive counterparts, and they are better expressed in the abstract mathematical formalism of this theory. The second, derived from reports by top-ranking physicists in the field, suggests that in order to grasp quantum mechanics, many physicists need to consider pictorial representations of the phenomena under study. However, pictures have no univocal correspondence with the formalism of this physical theory. The principle of complementarity, suggested by Niels Bohr, could accommodate the two conclusions, but this principle is not exempt from philosophical qualms. Still, a fair share of the research on teaching quantum physics at introductory levels has not yet considered these issues. The number of research and teaching designs based on bridges and analogies between quantum and classical concepts without consideration for the philosophical and conceptual implications of such a choice is considerable.

One of the main challenges related to introductory QT courses is thus to find a balanced approach through which to introduce the most basic quantum concepts while taking into account interpretational issues. As students attempt to make images of the quantum phenomena, another challenge arises which is related to the conceptual foundations of QT and the findings of the psychology of learning. Insofar as the history and philosophy of science contributions are concerned, they have a double role to play in teaching introductory QT. First, the introduction of the historical contexts in which QT was produced and was subsequently developed may bring flesh and blood to the introduction of a new scientific theory otherwise presented in a dry and disembodied manner. The second role implies having the teaching and the research of/on introductory quantum courses informed by the history and philosophy of the subject. This means that the educational choices and strategies should be informed by what we have learned from the ongoing controversy on the foundations of the discipline. This is the main focus of this paper. Indeed, naïve choices at the beginning of introductory courses on quantum physics using the chronological sequence of its production may be misleading insofar as such a syllabus may be technically challenging. It is enough to recall the technicalities behind the blackbody problem. Furthermore, a chronology could be pedagogically unsound as it may reinforce among the students undesirable bridges between classical and quantum concepts. If the chronological sequence is to be taught, in courses dedicated to the history of physics, for example, emphasis should be put on how scientists faced the epistemological obstacles hindering the development of the new theory.

We will argue that insofar as there is no privileged interpretation for quantum physics, there is no ideal way to teach it on an introductory course. However, we suggest that both teaching and research about QT in science education must make the interpretational choice used explicit. In addition, our point is that any course to teach QT should emphasize the strictly quantum features in order to prevent students from establishing undesirable links with classical concepts. While teaching focused on the mathematical formalism remains a choice, pictures may be exploited, but in this case complementarity should be explicitly and carefully introduced. Finally, we argue that the teaching of QT, maybe more than other areas in physics, must be informed by the history and philosophy of science. This paper is organized as follows: first, we discuss the history and philosophy lessons from the research on the foundations of QT. We then criticize the usual teaching of QT, and in the following section, we review the literature on introductory QT courses. Finally, before concluding, we analyze the role complementarity has played in the history of the teaching of this physical theory.

7.2 Lessons from Recent Research on Quantum Physics

In a world populated with transistors, lasers, and nuclear and atomic devices, it would be a platitude to emphasize the many and varied applications of the quantum theory since its inception around 1925–1927. In addition to its technological applications, QT has become a central part of training in physics and has brought with it wide-reaching philosophical implications. However, while the basic mathematical formalism has remained essentially the same since that time, our understanding of the implications of such a formalism has increased dramatically, in the last 50 years in particular. This increased knowledge has resulted from both theoretical and experimental developments enabling the testing of QT in extreme situations and of a new attitude towards its foundations and interpretations, the latter expressed in looking for its possible limitations.

However, from the inception of QT till the late 1960s, concerns about its foundations were mostly centered on the theoretical grounds. Some of the founding fathers of the new theory, such as Erwin Schrödinger, Albert Einstein, and Louis de Broglie, accepted neither some features of the new physical theory nor its interpretation in terms of a principle of complementarity suggested by Niels Bohr. Einstein and de Broglie criticized the abandonment of determinism, while Schrödinger and Einstein raised concerns about the idea of physical descriptions heavily depending on the means of observation, which amounted to giving up the kind of realism shared by most physicists at that time. Related to these concerns was the fact that the mathematical structure of the theory, through the principle of superposition of states, did not attribute well-defined physical properties to systems described by quantum theory. Thus, the state describing the spin projection of one electron says that this electron has both spin-up and spin-down and not one or the other. The weirdness of this quantum description results from the fact that in the world of everyday experience, objects, described by classical physics, have well-defined properties.

As physicists consider QT to be more basic than classical physics, the open problem is how to connect these two kinds of descriptions.

The problem was most clearly stated through the thought experiment now known as Schrödinger's cat. From a mathematically formal point of view, the issue was better stated by the mathematician John von Neumann who built the standard formalism of QT in terms of Hilbert vector space. Von Neumann acknowledged two kinds of evolution for the quantum states. According to him in the first kind, quantum states evolve in time ruled by Schrödinger's equation, which is a linear and deterministic process. During measurements, however, von Neumann suggested a second kind of evolution, which would be instantaneous, nonlinear, and nondeterministic (the "collapse of the wave function"). Since then, the so-called quantum measurement problem, in the terms suggested by von Neumann, has become a lasting ghost haunting the foundations of quantum theory.

Since the 1950s complementarity has no longer reigned alone because alternative interpretations have begun to appear. Two young American physicists, David Bohm and Hugh Everett, were the main protagonists challenging the received views on the interpretation of QT. Bohm criticized the abandonment of determinism and well-defined properties in the quantum domain. He built a model for electrons taking them as bodies with a position and momentum simultaneously well defined and was able to reproduce results obtained by QT in the nonrelativistic domain. His interpretation received both the technical name of "hidden variables" and the more philosophically inclined "causal interpretation." Everett built his interpretation, later entitled "many worlds," dispensing with the second kind of evolution of quantum states that von Neumann had taught would govern measurements. Thus, for Everett measurement was ruled by the same mathematical machinery of Schrödinger's equation. In particular, Everett disliked the complementarity assumption that quantum physics requires the use of classical concepts while limiting their use in the quantum domain as certain pairs of these concepts are complementary but mutually exclusive.

Since then the number of alternative interpretations of QT has grown. However, while they have become an industry for physicists and philosophers, populating many technical journals and books, they are conspicuously absent from physics teaching and most of the research on physics teaching.[2] The very existence of several interpretations of QT seems to be an inconvenient truth for the teaching of physics. The problem is that most of these alternative interpretations lead to the same experimental predictions at least in the nonrelativistic domain. Philosophers, logicians, and historians, however, are familiar with this kind of issue. Indeed, the

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[2] Short introductions to most of these interpretations may be obtained in Greenberger et al. (2009). This compendium includes the following interpretations: Bohm interpretation, Bohmian mechanics, complementarity principle, consistent histories, Copenhagen interpretation, GRW theory, hidden variables models of quantum mechanics, Ithaca interpretation, many worlds interpretation, modal interpretations, Orthodox interpretation, probabilistic interpretation, and transactional interpretation. While there is some redundancy in this list, it is not comprehensive; one could still include, for instance, stochastic interpretation, ensemble interpretation, and Montevideo interpretation. Indeed, this list has been growing in recent decades.

plethora of quantum interpretations is one of the best examples of the so-called Duhem-Quine thesis: the underdetermination of theories by the empirical data.[3]

While these theoretical developments dug deep into the foundations of quantum physics, it was the possibility of translating some of these issues to the laboratory benches that expanded our knowledge of the quantum world most, as we will see. No case is more telling than the statement that local realism is not compatible with QT predictions. The problem may be traced back to 1935 when Einstein, Podolsky, and Rosen suggested a *Gedankenexperiment* to demonstrate the incompleteness of QT and which Bohr rebutted. The issue was shelved until the middle of the sixties when John Bell realized that quantum physics predictions could be contrasted with any theory sharing the same 1935 assumptions of Einstein. Einstein professed a kind of philosophical realism meaning that physical objects should have well-defined properties independent of them being observed or not. In addition he assumed that no measurement of a system could change the state of a distant system, unless, of course, there is an interaction between these two systems propagating with a speed less or equal to light. It is the merit of Bell to have isolated in Einstein's reasoning such assumptions and to have managed them in order to show that as trivial as these assumptions may be, some quantum predictions do not confirm them. This is what we now call Bell's theorem. No local hidden variable theory can reproduce all quantum physics results. The reference to hidden variable theories is reminiscent of the historical context in which such a theorem emerged: the attempts to change quantum theory in order to obtain the description of systems with well-defined properties by introducing additional hidden variables in comparison with standard QT.[4]

"Bell's theorem changed the nature of the debate." Alain Aspect's words are now familiar to physicists. According to Aspect,

> In a simple and illuminating paper, Bell proved that Einstein's point of view (local realism) leads to algebraic predictions (the celebrated Bell's inequality) that are contradicted by the quantum –mechanical predictions for an EPR *gedanken* experiment involving several polarizer orientations. The issue was no longer a matter of taste, or epistemological position: it was a quantitative question that could be answered experimentally, at least in principle. (Aspect 1999, p. 189)

The creation of Bell's theorem was only the preamble to many thrilling activities in the last 50 years. It could have been the case that quantum predictions do not hold for distances longer than the molecular and atomic and in the end local realism

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[3] The case of quantum physics in relation to this philosophical thesis is discussed in Cushing (1999, pp. 199–203). A general discussion of the Duhem-Quine thesis may be found in Harding (1976).

[4] We chose to present the issue of completeness of QT in terms of Bell's theorem and its conflict between QT and local hidden variables or local realism. This choice was due to the influence of this approach on mainstream physics leading, through theory and experiments, to the identification of entanglement as a key quantum physical effect (Shimony 2009). Other approaches, however, are possible. A fine epistemological analysis of Einstein's assumptions would lead us, according to Howard (1985), to identify them as separability (mutually independent existence of spatially distant things) and locality. Another possibility is the Kochen-Specker theorem, formulated in 1967, which contrasts QT with non-contextuality; however, the impact of this theorem in experimental physics has been scant (Held 2012).

could prevail as a very reasonable assumption. In any case, in 1969 physicists such as John Clauser and Abner Shimony realized that the available experimental results could not check the double choice implied in Bell's theorem: either quantum theory or local realism. Since then, a string of experiments have been carried out leading to the confirmation of this weird quantum property: quantum nonlocality keeps its validity even for distances as far as a hundred kilometers as recent experiments by Anton Zeilinger and his team have confirmed. In the early stages of these experiments, the most revealing was that carried out by Alain Aspect and his team, who were able to change the experimental setting while the photons were in flight in order to prevent the working of any unknown interaction among the pair of photons or devices with a lower speed than that of light. Most of these experiments have been conducted with photons. In the first one, John Clauser used pairs of photons coming from atomic decay with atoms excited by thermal light. This source of excitation was then replaced by new tuning lasers, which dramatically improved the accuracy of the results. Finally, a new source of photon pairs began to be used in the late 1980s, photons from parametric down conversion which occurs when a laser beam crosses certain nonlinear crystals. This new source exponentially increased the experimental possibilities, and it has formed the basis of the impressive number of experiments on entanglement in the last two decades.[5]

The string of experiments on Bell's theorem have created a widely shared feeling among physicists that local realism should be abandoned even considering that more precise tests can be done in the future, in particular improving the efficiency of photodetectors. This has led physicists to unearth the term entanglement, coined by Schrödinger in 1935, to name the new quantum physical property. Indeed, though many terms are used to describe the same phenomenon, while with subtle differences, entanglement has prevailed as the brand new physical effect. The feeling that local realism should be abandoned had a strong philosophical implication at first, as stated by Clauser and Shimony as early as 1978: "either one must totally abandon the realistic philosophy of most working scientists, or dramatically revise our concept of space-time" (Clauser and Shimony 1978, p. 1881). Later on, experimental physics began to probe this dilemma. According to Aspect (2007, p. 866), "The experimental violation of mathematical relations known as Bell's inequalities sounded the death-knell of Einstein's idea of 'local realism' in quantum mechanics. But which concept, locality or realism, is the problem?" He was then commenting upon an experiment in which Zeilinger's team found violations of Leggett's inequalities, a variant of Bell's inequalities, which were formulated in order to exhibit the experimental contrast between quantum theory and even some classes of nonlocal realistic theories (Gröblacher et al. 2007). It was not yet the full-blown dilemma announced by Clauser, Shimony, and Aspect, but it was an example of what Shimony has called "experimental metaphysics," that is, theoretical and experimental research in the foundations of physics with huge philosophical implications.

Philosophy and basic science were not the sole domains in which Bell's theorem caused a stir. Nowadays entanglement is at the core of blossoming research in

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[5] On the early experiments on Bell's theorem, see Freire (2006).

quantum information as scientists and engineers attempt to harness quantum phenomena for more reliable cryptography and for speedier information processing. For those physicists and philosophers who are interested in a better understanding of the kind of world described by quantum physics, as well as for physics teachers, entanglement brought with it a new challenge: how to cope with the world view implied by this weird quantum property. For physics teachers, the challenge is further enhanced; if the purpose of this teaching is not only to hone calculus skills, how can an understanding of this seminal quantum property be conveyed if neither an intuitive perception nor a clear image of it can be presented to students?

Entanglement may be the most telling example, but it is not alone among the achievements of our understanding of QT in the last half century. An old quantum prediction, particles obeying Bose-Einstein statistics at low temperatures tend to gather in the same state, has now been confirmed by Bose-Einstein condensates in laboratories, which assured Eric Cornell, Wolfgang Ketterle, and Carl Wieman the 2001 Physics Nobel Prize. Behind this experimental feat was a technical trick: the use of lasers to cool atoms, a technique developed by Steven Chu, Claude Cohen-Tannoudji, and William Philips, also awarded the 1997 Nobel Prize in physics. As late as the 1950s and 1960s, Richard Feynman needed to use an idealized experiment of a double slit to convey the message of the wave-particle duality in his famous lectures, exactly as Einstein and Bohr in the 1930s had when they discussed the epistemological lessons from the quantum. From the 1980s on, however, physicists were able to manipulate photons, electrons, neutrons, and atoms one by one, making thus all these idealized experiments real.

Theoretical developments combined with experimental advances have also marked this last half century. The creation of the laser in 1960, in itself a quantum phenomenon, required theoretical improvements. One of the most impressive was that of Roy Glauber who created what we now call Glauber's coherent states, a useful tool for describing radiation in the domain of single photons. Glauber's predictions, later corroborated by the photon "anti-bunching" tests, became a key device in the toolkit of a new discipline: quantum optics, which solved a lasting controversy about the real need for the concept of photon. For all practical purposes, until the early 1960s, a full quantum treatment of light had led to the same predictions as semiclassical approaches, but the latter could not explain the "anti-bunching." Glauber was awarded the 2005 Nobel Prize for his achievements. In the 1980s physicists such as H. Dieter Zeh, Erich Joos, Anthony Leggett, Amir Caldeira, and Wojciech Zurek learned to deal with the transitions from states theoretically described by quantum superpositions to those which can be described by classical statistics mixtures, a theoretical treatment baptized decoherence. While decoherence shed some light on the old quantum measurement problem, it remained unsolved. It was in the following decade that Serge Haroche was able to push this treatment into the laboratory creating the first real analogues of systems such as Schrödinger's cat, that is, to see in the labs how, in a predicted time interval, a system described by a quantum superposition loses its quantum coherence. Again, this field of research is nowadays at the core of current research in quantum information. Earlier, in 1957, Yakir Aharonov and David Bohm had shown that quantum phenomena exhibit topological properties which can hardly be reconciled with our view of space-time as the arena for phenomena in physics. This kind of prediction is now well confirmed and enlarged by what is called Berry's phases. While this list of scientific deeds is not comprehensive, it is enough for our purposes.[6]

One may consistently argue that all these novelties are implicit in the mathematical quantum formalism. However, most of these achievements resulted from the ongoing controversy about interpretations of quantum physics and its basic concepts. Furthermore, an important part of this development was scientists' discomfort with the conceptual implications of this theory. For this reason one may also argue that a better understanding of QT was gained from the work of quantum dissidents. By using this label (Freire 2009), we are saying that they worked on the foundations of this theory, which was outside mainstream physics, and were critics of the complementarity view. A list of these dissidents could include some from the older generation, such as Einstein, but mainly those from the newer generation of physicists, such as Bohm, Everett, Bell, Clauser, and Shimony. However, QT has survived their criticisms and their related experimental tests. It is now time to extract the lessons both from the role played by the quantum dissidents and the amount of theoretical and experimental work already done. The teaching of introductory quantum physics courses could benefit from these lessons.

The new generations of physicists have learned that the object of QT must be described by its own quantum mathematical formalism and that no independent assumption, as reasonable as it may seem, can be previously assumed. This practical and epistemological lesson is bold in meaning because this formalism, embedded as it is in a very abstract mathematical structure, is impossible to grasp through pictures or mental images. However, there is one way to avoid this. Images of phenomena, such as the classical wave and particle, can be used, but by doing so, we are obliged to explicitly use Bohr's complementarity principle, a point to which we will return later.

From the history of the research on the foundations of QT in the last half century, we exemplify the previous lesson with one case—Aspect's 1986 experiment with wave-particle duality for single photons—chosen because of the clear-cut conclusions of its authors.[7] At the end of the 1970s, Aspect realized that the source he was using for experiments with Bell's theorem was delivering single photons as described by quantum optics.[8] The crucial point for him was that all previous

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[6] For brief introductions to these topics, see Greenberger et al. (2009). On the debates on the concept of photon, see Silva and Freire (2013). The Concept of the Photon in Question: The Controversy Surrounding the HBT Effect circa 1956–1958, *Historical Studies in the Natural Sciences*, forthcoming; on quantum optics, see Bromberg (2006); for historical studies on decoherence, see Camilleri (2009b) and Freitas (2012), The many ways to decoherence, unpublished monograph.

[7] For experiments with single electrons in the two-slit interference experiments and debates about their interpretations and dispute of priorities, see Rosa (2012). As an example of the ongoing controversy surrounding the foundations of quantum physics, Marshall and Santos (1987) considered that Aspect's 1986 typical quantum results could be compatible with the classical wave theory of light as the latter were interpreted in terms of Stochastic Optics.

[8] Alain Aspect, interview with O. Freire and I. Silva, 16 December 2010 and 19 January 2011, American Institute of Physics.

experiments with “single photons,” which dated back to Taylor in 1909, could not be quantum mechanically described as single-photon impulsions. Indeed, those very attenuated sources which gave just one photon in the experimental setting on average were not single-photon states such as the source Aspect was using. After presenting his results, Aspect (Grangier et al. 1986, p. 178) interpreted them in two different manners. The first was based on complementarity; however, he was cautious about it: “if we want to use classical concepts, or pictures, to interpret these experiments, we must use a particle picture for the first one, […] on the contrary, we are compelled to use a wave picture, to interpret the second experiment. Of course, the two complementary descriptions correspond to mutually exclusive experimental set-ups.” Aspect’s inclination was towards the second kind of explanation he had suggested. It was an explanation based on a direct interpretation of the quantum mathematical formalism, without appealing to pictures, using concepts that had just emerged in quantum optics: “from the point of view of quantum optics, we will rather emphasize that we have demonstrated a situation with some properties of a ‘single-photon state’.”

Three years later, discussing the same results, Aspect (Aspect et al. 1989, p. 128) went further in his epistemological choices. After presenting the explanation with complementary classical concepts, he added: “the logical conflict between these two pictures applied to the same light impulses constitute one of most serious conceptual problem of quantum mechanics.” Then he recalled that the experimental setups were incompatible and that this incompatibility was presented by Bohr as an element of coherence of QT. While presenting the second explanation, he remarked that such a logical conflict only appears if one appeals to classical concepts, such as wave and particle. And yet his choices were favorable to the second type of explanation he had suggested:

> … if, on the contrary, one is restrained to the quantum mechanics formalism, the descriptions of the light impulses are the same. It is the same state vector (the same density matrix) that one must use for each experiment. The observable changes but not the description of light. (Aspect et al. 1989, p. 128)

Thus the quantum formalism is self-sufficient, it describes both experiments without appealing to pictures or classical concepts.[9]

If the history of the research in the foundations of QT seems to favor the interpretational trend which takes only the quantum formalism to grasp quantum phenomena, as suggested by Michel Paty (1999), this same history also suggests another lesson. Indeed, it seems to us that the need for pictures/images, thus of classical concepts, persists even among the best working physicists.[10] Here the case

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[9] Incidentally, we remark that Aspect considers wave-particle duality for single photons the best way to introduce, both theoretically and experimentally, the full quantum treatment of light on optics courses. See his proposal in (Jacques et al. 2005).

[10] We use image and picture as equivalent words. Psychology of learning uses image as picture may be associated with drawings. Physicists use both without distinction, while in QT, both are always associated to concepts from classical physics.

of John Clauser, who conducted the first experimental tests on Bell's theorem, is enlightening. Sharing his memories, he always disliked abstract reasoning:

> One of the problems I have, I'm very different from many physicists, which is both a blessing as well as a major impediment. I am not really a very good abstract mathematician or abstract thinker. Yes, I can conceptualize a Hilbert's Space, etc. I can work with it, I can sort of know what it is. But I can't really get intimate with it. I am really very much of a concrete thinker, and I really kind of need a model, or some way of visualizing something in physics. (Clauser 2002, p. 8)

Clauser's recollections may be useful for researchers in physics teaching dealing with the challenge of teaching introductory quantum physics. He goes on to say:

> There exists a set of numbers with algebraic structure of such and such, and we will define a particle as being something for which this operator commutes with that operator, etc. I haven't the foggiest idea what any of that means. But an electron is a charge density which may be Gaussian in shape and its shape, and it's about this big, and it's held together by various forces, and this is how the forces work that kind of hold it together. The difference between those two [concepts] are very dramatic differences of thinking. Now there's a whole class of physicists who can only think in the former method. I can only think in the latter mode. (Clauser 2002, p. 9)

We should add that insofar as Clauser (2002) also disliked Bohr's complementarity, he felt enduring discomfort with usual presentations of quantum physics, a discomfort which is relevant for our discussion on the teaching of quantum physics.

Quantum theory has passed the most severe experimental tests ever imagined for a physical theory. However, this does not mean that corroborations of the quantum physics predictions, that is, predictions of QT mathematical formalism, have implied corroboration of only one interpretation of this formalism. Indeed, only local realistic theories come up against obstacles in those tests. Curiously, most of the alternative interpretations of QT include some form of quantum nonlocality insofar as most of them preserve the linear superposition which is intrinsic to the Hilbert space in the usual interpretation.[11]

Quantum theory is weird not only because of its concepts, such as those related to the abandonment of determinism and local realism, but also for its place in the history of physics. It is so strange that 80 years after its creation, its recasting process—where the notions of a theory are clarified and its terms improved (Lévy-Leblond 2003; Paty 1999, 2000)—remains unfinished. Although its mathematical machine is well established and its predictive power successful, the conceptual foundations of QT are still in debate. In fact, we now have a better understanding of what QT is mostly from the ongoing controversy on its interpretation and foundations.

Therefore, one lesson from the history of physics as regards the attempts to introduce quantum physics at more elementary levels is that we should take into account

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[11] The empirical equivalence of several QT interpretations in the nonrelativistic domain does not mean that all interpretations have been equally fruitful in the development of QT, in particular in the new field of quantum information. An interesting discussion on this aspect considering the case of "entanglement swapping" is Ferrero et al. (2012).

the peculiar situation of the existence of a tension between a strong consensus about the formalism of this physical theory and a meaningful dissension about its interpretation. Of course, physics students need first to learn the quantum physics formalism in order to grasp such a controversy, but at a certain moment, we should convey to them the very existence of such a controversy.

7.3 The Usual Teaching of Quantum Physics

As we have pointed, teaching QT is not an easy task because it is both technically and philosophically sensitive. Its teaching is quite different from other topics in physics. It is perhaps the only area that is most commonly introduced through the history of its origin. From the late nineteenth century and through the first half of the twentieth century, these topics include Planck's quantization of energy to explain the spectrum of black body radiation, Einstein's photons of light to explain the photoelectric effect, Bohr's energy levels in his model for the atom to explain atomic spectra, de Broglie's hypothesis of waves associated with electrons, Schrödinger's formulation of a wave equation for orbiting electrons, Heisenberg's introduction of an uncertainty principle, and Born's interpretation of the wave function in terms of probability.

This introduction is a typical example of what Kragh (1992) called the quasi-history, a mystical history used to convince students of a particular point of view, the only "rationale" possible reached by physicists in the past. It is worth stressing that this historical approach has been criticized (Cuppari et al. 1997; Fischler and Lichtfeldt 1992; Michelini et al. 2000) for reinforcing classical concepts in students' minds at a time when they should have been moving on to more appropriate quantum models.

Advanced courses, while dispensing with this historical tour, repeat the very same material again and again. For example, the infinite well used as a pedagogical example or as a model of a physical system is usually encountered by a physics student in the USA up to five courses before he or she graduates (Cataloglou and Robinett 2002). The typical approach in these advanced courses can be described as consisting of highly abstract rules and procedures (Shankar 1994), in part because the mathematical tools necessary for applying it, even in the simplest cases, are so different from other branches of physics that the trend to present quantum concepts as inseparable from its mathematical problems exists (Bohm 1989). Nevertheless, behind this uniformity, there is a greater variability than that found in other typical subjects in physics. There is a wider array of possible topics which one might consider as constituting the core ideas (perhaps because among physicists there is no consensus about which are the most fundamental ideas in quantum physics), and also unlike classical mechanics or electromagnetic theory, there is a wider variety of approaches to the teaching of QT, even at the undergraduate level.

We can find texts that stress the formal aspects, starting with the formalism of spin systems and Hilbert spaces, texts focusing on the Schrödinger's equation, and some that present semiclassical approaches. Across this diversity most of the traditional textbooks provide few, if any, physical insights. In fact, textbooks seem to privilege what one could call an instrumentalist view of QM or what Redhead (1987) named the "minimal instrumentalist interpretation," i.e., quantization algorithm, statistical algorithm plus the epistemological premise that "theories in physics are just devices for expressing regularities among observations." This kind of approach reduces the cognitive reach of the quantum theory and does not make its understanding any easier.

This "minimal instrumentalist interpretation" is so widespread among physics teachers that several authors consider that most of the difficulties students have with quantum physics are related to its characteristic formalistic teaching that begins during introductory courses.[12] What are the factors that may have led to this kind of teaching? One seems to be, as just indicated, the intrinsic mathematical difficulty of quantum physics. But there are others. After the first period of its constitution, most physicists used QT machinery to study the microscopic world, without worrying about conceptual or interpretational questions (Heilbron 2001). This predominance of QT as a "calculating machine" may have been reinforced particularly in the USA because of the coexistence of theoretical and experimental physicists in the same departments, emphasizing experiments and applications, and the American trend to pragmatism (Schweber 1986).

The historian of physics David Kaiser also indicates another factor related to pedagogical choices during Cold War times. In the two decades after the war, the USA underwent a surge in the number of physics students which made it necessary to take some pedagogical decisions that specially affected the teaching of QT:

> Most physicists in the US recrafted the subject of quantum mechanics, accentuating elements that could be taught as quickly as possible, while quietly dropping the last vestiges of qualitative, interpretive musings that had occupied so much classroom time before the war. […] The goal of physics became to train 'quantum mechanics': students were to be less like otherworldly philosophers and more like engineers or mechanics of the atomic domain. (Kaiser 2007, p. 30)

This change has been reflected in the textbooks published since then,[13] with wonderful methods for doing almost any calculus about atoms; however, when it comes to the principles and interpretations of QM, they "are, almost without exception, simplistic and obscure at the same time" (Barton 1997). These approaches ultimately worked because, as we have seen, one lesson from recent history is that quantum concepts are strictly associated to the mathematical formalism.

Students are more than occasionally encouraged to approach the subject with the idea that it is almost impossible to understand it and that it is so completely different from other branches of physics that one's intuition is of little or no use. As an advanced student said, referring to his experience in QT: "It seems that there's this dogma among physicists, that you can't ask that question: What is it doing between

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[12] Fischler and Lichtfeldt (1992), Greca and Freire (2003), Johnston et al. (1998), and McKagan et al. (2008).

[13] In several countries, the most widely used textbooks in physics are American ones thus the spread of this approach.

point A and point B? 'You can't ask that!'" (Baily and Finkelstein 2010, p. 9). It is not surprising then that students dislike quantum theory and non-physics students try to avoid it. Many physics students, including graduates, despite seeing the same topics many times and successfully engaging in the mathematical machinery, constantly struggle to master its basic concepts, a problem that has been reported by several researchers (Cataloglou and Robinett 2002; Johnston et al. 1998; Singh 2001, 2006).

Despite the strength of the usual way of teaching QT, it has been challenged in recent years. It is not by chance that more than in other physics disciplines, it has increased the number of textbooks with new approaches. While it is beyond the scope of this paper to review the new batch of quantum physics textbooks, we give just a few examples of this trend. Griffiths' 2005 *Introduction to Quantum Mechanics* dedicates a chapter to the meaning of basic concepts and interpretational issues; Thaller's 2000 *Visual quantum mechanics* exploits simulations in wave mechanics; Greenstein and Zajonc's 1997 *The Quantum Challenge* includes many physical examples and makes direct connection to recent experimental results; and Omnès's 2000 *Comprendre la mécanique quantique* is the explicit defense of what he considers an updated interpretational view of quantum theory.

The wide recognition of how ubiquitous quantum physics has become in current technologies, how important it is for our understanding of nature and science at the present time, how fundamental it have been considered for physics, and the role it has played on the cultural scene have led to an increased interest in studying its teaching in the last two decades. Motivation for these studies derives thus from the need to convey quantum concepts not only to physics students but also to other science and engineering students, and they attempt to understand how to attract students to study quantum physics instead of running away from it. This kind of research has addressed students' difficulties with quantum concepts, surveys, and didactic strategies to better introduce quantum physics in physics introductory courses at universities—for physics, chemistry, and engineering students—and at high school level.[14] Being technically and philosophically sensitive, quantum physics poses some unique and interesting challenges to its teachers. Should students develop an understanding of the mathematics without worrying about the philosophical implications of the theory? Should the historical development of quantum theory be included in the syllabuses? Should we use or avoid classical or semiclassical analogies to help students grasp quantum concepts?

7.4 Proposals for Introductory Quantum Physics

What do the new proposals for teaching quantum physics which have emerged from research into science education suggest to improve students' understanding of quantum concepts? We have reviewed the literature published in physics education

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[14] Greca and Freire (2003), Hadzidaki (2008a, b), McDermott and Redish (1999), and Wuttiprom et al. (2009).

from 2000 to 2011[15] and found 32 articles that tackle new forms of introducing QT topics at certain educational levels. Although only 11 of them mentioned the outcome of the implementation, in general they were very well received by the students but with varied conceptual improvements. Many of the papers, amounting to 10, are related to the use of the history and philosophy of science, using proper historical reconstruction (Barnes et al. 2004; Níaz et al. 2010), conceptual discussion of thought experiments (Velentzas et al. 2007; Velentzas and Halkia 2011), discussion of philosophical, epistemological and ontological issues concerning quantum physics through historical controversial issues—EPR, Heisenberg microscope—(Hadzidaki 2008a, b; Karakostas and Hadzidaki 2005; Pospievich 2003), or using QT as a tool for improving the views preservice teachers have about the nature of science (Kalkanis et al. 2003; Nashon et al. 2008).

Most of works using historical emphasis dealt with high school students and preservice teachers. In general, these works try to contextualize quantum physics in an updated historical and epistemological framework and in this way—as opposed to the "traditional" historical approach—help learners to reorganize and enhance their initial knowledge. Kalkanis et al. (2003, p. 270) propose, for example, the juxtaposition of representative models of conceptual systems of quantum and classical physics. Thus, instead of avoiding reference to classical physics, their strategy reveals the totally different worldview and thought patterns underlying the interpretation of macroscopic and microscopic phenomena. They used Bohr's atomic model, for example, in order to make the deep conceptual differences between classical and quantum physics concrete. Instead of avoiding the dualistic descriptions, they aimed to reveal the inner meaning of the complementarity principle. We can include in this category an article that stresses the introduction of quantum physics through unusual interpretations, such as the Bohmian one, as a useful tool to illustrate the relationship between classical and quantum physics (Passon 2004).

The second most frequently proposed strategy, with eight papers, is the use of simulations, computer animations, or games to improve the intuitive understanding of abstract quantum concepts, especially for students with a limited science and mathematics background or for advanced students who have seen quantum concepts traditionally—that is, only in a mathematical way.[16] These simulations, some of which integrate hands-on activities, attempt to build intuition for the abstract principles of QT through visualization in introductory physics, with precursors in the Quantum physics series of the Lawrence Berkeley Lab (Gottfried 1978) and the programs Eisberg (1976) designed for visualizing wave functions with the early programmable calculators. This "wavy" tendency can be seen in the names of some of the typical simulations—quantum tunneling and wave packets, quantum wave

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[15] We have researched articles from the period 2000–2011 that tackle physics education in any level in the following journals: *American Journal of Physics*, *European Journal of Physics, International Journal of Science Education*, *Journal of Research in Science Teaching*, *Physical Review Letters – Special Topics, Research in Science Education, Science Education*, and *Science & Education*.

[16] For example, Goff (2006), Magalhães and Vasconcelos (2006), McKagan et al. (2008), Singh (2008), and Zollman et al. (2002).

interference, matter waves, probabilities and wave functions, and wave functions and energies in atoms. However, wave interpretations without reference to complementarity have not endured in the history of the research on the foundations of quantum physics, and none of these papers mentioned the complementary principle. Finally, it is worth stressing that several of the proposals not included in this group also make use of some computer simulations.

In third place, with seven papers, there are different "technical" approaches (deformation quantization, evolution operator method, field theory, computer algebra systems), most of them for advanced courses in physics (e.g., García Quijás and Arévalo Aguilar 2007; Hirshfeld and Henselder 2002), which will not be commented on here as we are dealing with introductory quantum physics courses. Finally, in fourth place, there are five papers with proposals that share an emphasis on quantum features of the systems, rather than searching for classical or semiclassical analogies, using in general real-world applications or recent experimental advances.[17] These works are in consonance with the researchers linked to the area of quantum optics[18] who have stressed the relevance of introducing quantum concepts from the very beginning. From the experimental results about the foundations of QT obtained in the last 20 years, in general they tend to use very simple systems that show clear quantum behavior, leaving aside non-physics fictions such as the Heisenberg microscope.

So until the present time, science education researchers, although unanimous in rejecting the traditional "quasi-historical" introduction or the formal one, have given quite different answers to our questions about how to introduce quantum concepts. It is worth stressing that we do not have any strong evidence for advocating one way or another because few of the proposals have been tested. Thus some of our arguments from now on derive from the recent history of the research on the foundations of quantum physics as well as from empirical evidence obtained in science education research.

7.5 Quantum Theory Interpretations and the Research in Science Education

It is striking that, although all the papers emphasize the need to improve the conceptual understanding of quantum concepts, few of them clearly stated the interpretation of QT that is adopted. It seems as if the intense debate about the different interpretations, which is a conceptual debate, has yet to inform research into better ways of teaching quantum physics.

From the 32 papers found in the period 2000–2011, only 10 mention the existence of different possible interpretations. We have Bohr's realist interpretation (Hadzidaki

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[17] Carr and McKagan (2009), Greca and Freire (2003), Holbrow et al. (2002), and Müller and Wiesner (2002).

[18] For example, Barton (1997), Jacques et al. (2005), Schenzle (1996), and Zeilinger (1999).

2008a, b; Karakostas and Hadzidaki 2005), the statistical ensemble interpretation (Müller and Wiesner 2002), the Copenhagen interpretation (Barnes et al. 2004; Kalkanis et al. 2003), an orthodox but realist interpretation (Greca and Freire 2003), the Bohmian dualistic interpretation (Passon 2004), and the interpretation of the quantum states as potentialities (Pospievich 2003).[19] Of these, three belong to the same research group and six have been published in *Science & Education*, a journal that stresses the contributions of philosophy and history to science education.

It is interesting to note that, except for two, all of them can be included in the spectrum of the realistic interpretations—that is, interpretations that move away from the epistemological position of the Copenhagen interpretation and that give an objective character to the concept of state of a quantum system and thus are less dependent on the measurement process. It seems that realistic interpretations are seen by science education researchers as the best interpretational option for introducing quantum physics to students. For example, we have argued (Greca and Freire 2003) that our aim to help students to develop mental models whose results—predictions and explanations—coincide with those accepted by physicists' community has led us to look for a realist interpretation of QT. This is because our remarks on scientific practice reflect Bunge's position (2003) when he writes that "the realism [is] inherent in both common sense and the practice of science." This trend towards realistic interpretations is coincident with the predominant epistemological view maintained by the physicists who worked in the foundations of QT in the 1970s (Freire 2009, p. 288).[20]

These realistic interpretations consider quantum states (represented by wave functions, state vectors) in general as having a physical reality independent of measurements. Bohm and Hiley (1988) attributed this view to von Neumann while opposing Bohr's view, because the latter valued the role of measurement excessively, through the idea of wholeness of the system and the measurement apparatus. As a matter of fact, several physicists and philosophers—such as Fock, Bunge, Lévy-Leblond, and Paty—have suggested similar ideas, though there are some relevant differences among them. An illustration of such differences is the case of the Soviet physicist Vladimir Fock, who combined defense of complementarity with the attribution of physical reality to the objects of quantum physics (Graham 1993, pp. 112–117).

Mario Bunge, for example, considers the possibility of a realistic reinterpretation of standard QT, a subtle but philosophically meaningful different interpretation from the Copenhagen interpretation. As he writes:

> … instead of interpreting Born's postulate in terms of the probability of *finding* the quanton in question within the volume element Δv, the realist will say […] that the probability in question is the likelihood of the quanton's *presence* in the given region. (Bunge 2003, p. 462)

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[19] We have named the interpretations as stated by the authors, without evaluating superpositions or duplications.

[20] The categorization we have used is a rough approximation, useful only to grasp analogies between physics teaching research and physics research. Realism and objectivity are not univocally defined in philosophy of science, and quantum physics practice has brought meaningful constraints to the use of these terms.

The Canadian-Argentinian philosopher was also among the first to use a new terminology—quantons—to describe QT as having an object without a measurement process, essentially distinct from those of classical physics. In a textbook with an innovative didactic approach to introductory QT courses, Lévy-Leblond and Balibar (1990, p. 69) support similar epistemological premises. According to them, "it is, therefore, necessary to acknowledge that we have here a different kind of an entity, one that is specifically quantum. For this reason we name them *quantons*, even though this nomenclature is not yet universally adopted." More recently, Michel Paty has developed this idea:

> in terms of an extension of the meaning given to the concepts of *physical state and physical quantity* of a system, which would allow, without any theoretical change in QT, to speak consistently of *real quantum systems* as having definite *physical properties*. (Paty 1999, p. 376)

The philosophical key to this generalization was found by Paty (2000) in a historical and epistemological analysis of the "legitimacy of mathematization in physics"; this generalization suggesting "an extension of meaning for the concept of physical magnitude that puts emphasis on its relational and structural aspects rather than restraining it to a simple 'numerically valued' conception." According to the French philosopher, such a generalization could be useful not only for QT but also for the case of dynamic systems and quantum gravity. While essentially based on his philosophical analysis, Paty argues using some issues related more directly to scientific practice. He quotes the recent experimental confirmations of QT to maintain that the working physicist, in a spontaneous way, refers to quantum theory as "a fundamental theory about a given *world of objects*" and that this spontaneous perception only faces difficulties when it focuses the "*transition* from this *quantum domain to the classical one* that of measuring apparatuses." The list of supporters of realism in quantum physics is far from being comprehensive. However, while the quantum controversy may be seen as one more chapter in the dispute between realism and instrumentalism that has characterized the whole history of physics, the history of QT framed the debate in news terms. Indeed, the experience gained with QT disavowed many features associated with the usual realistic view. If this view has a future in the philosophy of physics, and we think it has, it needs to be accommodated with epistemological and conceptual lessons from QT.

The insensitivity to the philosophical choices seen in the physics teaching papers we have analyzed may have biased some of their research results. For example, McKagan et al. (2010) reported that, in order to construct a conceptual survey on QT, they were not able to find any version of a question trying to address the wave-particle duality that the faculty agreed upon as the "correct" answer. It is also evident that the didactic strategies will be different depending on the interpretational choices and that the uncritical adoption of one of them—which occurs when it is not clearly stated—may have undesirable consequences. For example, the proposals that attempt to represent in a "more displayable" way some quantum concepts using simulations tend implicitly towards a wavy interpretation that by its nature may reinforce links with classical physics. Such proposals may anchor in the classic ideas students already have, making them stronger and prevent them from gaining a better understanding of quantum concepts. This happens, for example, in the difficulties students have replacing the idea of electromagnetic wave with probability wave (Greca and Freire 2003): many students consider the probability density representation to be a representation of movement. Similar results were found among chemistry students introduced to the wavy model of the atom, who understand the concept of orbital as a "space" and not as a mathematical function (Tsaparlis and Papaphotis 2009).

Clauser (2002), although recognizing the use of images for interpreting physics concepts, is aware of the pitfalls that images associated with the wavy model may present:

> In quantum mechanics, the books all make this seem like simple wave mechanics, i.e. what you would see – a direct analogy with waves on the surface of a pond. And they show pictures. […] And then even worse, they say, 'Okay. A particle, we can represent kind of as a wave packet,' whatever that means. […] propagating in real space. […] Now consider a two particle case. Ψ is no longer a functions of x, y, z, and t. It's a function of x_1, y_1, z_1, x_2, y_2, z_2. Has space and time grown? […] So if I couldn't do it for four, three, two particles, I shouldn't have done it for one particle either. […] Which means this whole idea of wave packets that all of the books put in there is to try and make you feel comfortable with it, all of those chapters, you might as well rip up and throw them away because they are wrong because that's not the correct conceptual model. (Clauser 2002, p. 14)

We are not rejecting the use of images or materials that may make quantum concepts for the teaching of quantum physics more visible. In fact, by applying cognitive psychology to research in science education, it is possible to find evidence that many college students use imagistic mental models to make sense of physics concepts (Greca and Moreira 1997, 2002); that is, they need to "visualize" what is happening in order to understand. It is worth stressing that this use of imagistic representations can be found in the work of great physicists such as Faraday or Maxwell (Nersessian 1992). The point is that the use of images in QT must necessarily refer to the complementarity ideas, as indicated in Aspect's explanation. Therefore, students must be thoughtfully introduced to the complementarity principle. However, there is an obstacle: complementarity has virtually disappeared from teaching and research in science teaching.

7.6 Complementarity in Science Education Research

From the 32 papers we have researched, only 10 refer to the existence of different possible interpretations and 9 among these papers cite the existence of the complementarity view. Two of them (Greca and Freire 2003 and Passon 2004) do not consider its potential usefulness. Interestingly enough, other papers which report surveys or identify students' learning difficulties using the Copenhagen interpretation do not make use of the concept of complementarity. This strange finding comes, however, as no surprise to those who know the history of quantum physics teaching.

At the end of 1927 the complementarity view was clearly the most influential among the founding fathers of quantum physics. It had gathered Heisenberg, Pauli, Jordan, and Born, in addition to Bohr, on its side while the remaining critics, such as Einstein, de Broglie, and Schrödinger, supported different views on the subject. Soon, de Broglie aligned himself with the complementarity camp. The historian of physics Max Jammer (1974, p. 250) called the period from the creation of quantum theory until the 1950s the times of the unchallenged monocracy of the Copenhagen school.[21] However, adhesion to this monocracy was weaker than this term may suggest. Its diffusion outside Germany and Denmark was not without difficulties (Heilbron 2001; Schweber 1986), as we have already seen. As a matter of fact, the complementarity view was absent from the one of the most powerful tools in the training of physicists, namely, textbooks. Kragh (1999, p. 211) remarked that only 8 out of the 43 quantum physics textbooks published between 1928 and 1937 mentioned the complementarity principle while 40 cited the uncertainty principle. Despite how central complementarity was in Bohr's interpretation of quantum physics, "most textbook authors, even if sympathetic to Bohr's ideas, found it difficult to include and justify a section on complementarity." Kragh noted that Dirac, the author of one of the most influential textbooks ever written, while closely connected to the supporters of the Copenhagen interpretation and having great respect for Bohr, "did not see any point in all the talk about complementarity. It did not result in new equations and could not be used for the calculations that Dirac tended to identify with physics" (Kragh 1999, p. 211). Indeed, even in most current textbooks when some reference to complementarity is made, it is restricted to the mutual exclusion between wave and particle representations.

The absence of complementarity in the culture of practicing physicists was so conspicuous that Bohr's biographer, the physicist and historian of physics Abraham Pais, announced in the introduction of Bohr's biography that he was looking for a reason for such an absence (Pais 1991). However, Pais did not solve the riddle. One hint, not yet exploited by historians of science, concerns the reasons why Niels Bohr himself did not write a textbook in which complementarity was clearly presented. In the early 1950s, as the debates around the interpretation of the quantum were becoming a hot topic, Léon Rosenfeld, the physicist who was the enduring assistant of Bohr for epistemological matters, acutely felt the need for such a book:

> There is not a single textbook of quantum mechanics in any language in which the principles of this fundamental discipline are adequately treated, with proper consideration of the role of measurements to define the use of classical concepts in the quantal description. (Rosenfeld 1957, apud Osnaghi et al. 2009, p. 99)

At the same time, Rosenfeld unsuccessfully urged Bohr to write it while reporting the interest around complementarity and the debates over the interpretation of quantum physics: "There is great interest in the topic among chemists and biologists, but

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[21] Recent studies, however, have shown both the diversity of perspectives behind the term "Copenhagen interpretation" and the context of its coinage, for example, Camilleri (2009a) and Howard (2004). See also Beller (1999) for the nuances among the founding fathers of QT which are usually smoothed over in the term Copenhagen interpretation.

there is no book that one can refer them to and that could protect them from the confusion created by Bohm, Landé, and other dilettantes." Rosenfeld concluded saying: "I will now do my bit here in Manchester by giving a lecture for chemists and biologists; but nothing can replace the book that *you* must write" (Rosenfeld 1957, apud Osnaghi et al. 2009, p. 99; emphasis in the original). Parodying "The book nobody read," a title used by the historian Owen Gingerich (2004) for the book in which he charted the readers of Copernicus' book in early modernity, "The book nobody wrote" is an open and interesting question on the vicissitudes of physics in the twentieth century.

And yet complementarity is being revived among practicing physicists, this time stripped of its heavy philosophical clothes and framed in the information turn arriving to quantum physics in recent years (Gleick 2011). Greenstein and Zajonc (1997), for instance, presented it as the mutually exclusive availability of information among certain ways or transitions. Physicists such as Anton Zelinger, Seth Lloyd, John Archibal Wheeler, and Wojciech Zurek have argued for putting information as a key concept into the foundations of quantum theory. Of course, it can be said that changing classical concepts for information is just a change of wording. However, most would agree that understanding information from a conceptual and epistemological perspective is fundamental to the current challenges in science in general, not only in quantum physics.

7.7 Conclusion: Lessons from History and Philosophy for the Teaching of QT

In the same way as there is no privileged interpretation for quantum physics, there is no ideal way for its introductory teaching at undergraduate level. There is, however, a varied spectrum of options available. The analysis we have developed in this paper privileges the following possibilities that we consider informed by the history and philosophy of science and the teaching experience. The first thing that follows from the arguments we have presented here is that QT teaching and research about QT in science education must make interpretational choices explicit and that choice must be justified or defended. Not doing so not only may reduce the scope of the research results but also the possibilities of the teaching strategies, as introducing elements that are not explicitly explained to students may confuse them. The second point is that any proposal for teaching QT should emphasize the strictly quantum features in order to prevent students from establishing undesirable links with classical concepts.

There are varied options from this point on. The teaching of QT may emphasize the formalism, without worrying about the ultimate ontological status of the mathematical terms. Of course, introductory courses have to make use of an adequate mathematical level. So that a balance between rigor and facilitation may be reached this may be illustrated with the case of systems of two levels that can be treated with matrices and vectors. As we have seen, quantum formalism is self-sufficient, and there is a new generation of physicists, working in advanced quantum research areas, who seem not to need the classical counterpart to manipulate quantum mechanics with proficiency (Aspect et al. 1989; Zeilinger 1999). Along these lines the teaching should give prominence to quantum features such as the superposition principle and the measurement problem as well as effects such as quantum entanglement, quantum beatings, and decoherence in addition to the description of current research on these topics, which are relatively easy to grasp in a conceptual manner.

This is not only important for the understanding of quantum mechanics but also to motivate students to continue their studies on this subject. It is worth stressing that this way of introducing quantum mechanics can be compatible either with the realism or the instrumentalism in terms of epistemological views, as we have seen. The dispute between instrumentalism and realism has accompanied the history of science—the Galilean fight for one of the chief world systems being the most well-known example—and the teaching of quantum mechanics is not the space for settling such a philosophical issue. However, students in introductory physics courses should be introduced to such a pervasive dilemma, and quantum physics courses may be a privileged space for doing so.

Another interesting option could be the use of images (in the form of simulations or other) in order to make quantum concepts more understandable. As we have seen, both from the report of first ranking physicists and from the research in science education informed by cognitive psychology, many students may need concrete models or some way of visualizing the abstract mathematical structure to grasp quantum concepts. Such students, who are perhaps more numerous outside physics courses (e.g., engineering, chemistry, and biology students), may profit from this approach. However, if this approach is used, it is necessary seriously and explicitly to introduce complementarity in the explanation of the right quantum use of these images. Finally, it is possible to combine the formal approach with the introduction of the complementarity view, as we have seen in Aspect's explanation of his experiment on the dual nature of single photons. Perhaps it is time to revive this view in science education research, but in this case, it should not be reduced to the wave-particle duality. In Bohr's own terms, wave-particle duality is just the particular case of a wider view:

> Information regarding the behaviour of an atomic object obtained under definite experimental conditions may […] be adequately characterized as complementary to any information about the same object obtained by some other experimental arrangement excluding the fulfillment of the first conditions. Although such kinds of information cannot be combined into a single picture by means of ordinary concepts, they represent indeed equally essential aspects of any knowledge of the object in question which can be obtained in this domain. (Bohr 1987, p. 26)

Indeed, if teachers and researchers choose to introduce complementarity in QT teaching and education research, it should be properly introduced from the conceptual point of view, as done in the current research on QT or philosophical studies on Bohr's thoughts, which opens another venue for contributions from history and philosophy of science to science education.

Our analysis shows that the infusion of historical elements through the introduction of cases from old quantum physics (blackbody problem, photoelectric effect, atomic model) should be avoided. This is partly because the most important steps in the early construction of QT do not show the specific quantum features in a clear-cut manner, and some of them are very complex for students to understand in introductory courses. In contrast, new experiments are conceptually more accessible and can also be reproduced in undergraduate physics laboratories (see, e.g., Dehlinger and Mitchell 2002; Galvez et al. 2005; Thorn et al. 2004). An analogous process happened with the teaching of classical mechanics: the astronomical calculus that led to the classic (and also not intuitive) form of seeing the world is not present in the introductory teaching of classical mechanics. We begin with very simple examples and models in order to help students understand the basic concepts. In courses which are more focused on the history of science, these astronomical examples may have their space when classical mechanics is concerned. But in the QT case, presentation of topics from old quantum physics should emphasize the kind of problem physicists faced and the type of limitations they introduced.

Finally, we would like to stress that the teaching of QT, maybe more than other subject areas in physics, must be informed by the history and philosophy of science. Controversy on its foundations and interpretations has been one of the longest controversies in the history of science and students should be informed of this fact. References to this interpretational debate may bring to the forefront of science education nonconformists who fought against well-established views even putting their professional careers in danger (Freire 2009). This may illuminate the theoretical and experimental developments—Bell's theorem is the best case which brought this debate into mainstream physics—and the current blooming research that has emerged from that controversy. Thus, quantum physics is a very lively example of physics as a human and social product, and we should not exempt students from the presentation of these developments that humanize science.[22]

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[22] Exposing students to an open scientific controversy may bring some discomfort to physics teachers as this may weaken the dogmatic feature some think it is inseparable to science training. The question reminds us of an old dilemma well posed by Stephen Brush (1974, p. 1170): "Should the History of Science Be Rated X?" In this now classic paper, Brush suggests to science teachers this dilemma in the following terms: "I suggest that the teacher who wants to indoctrinate his students in the traditional role of the scientist as a neutral fact finder should not use historical materials of the kind now being prepared by historians of science: they will not serve his purposes." Then, he continues, "on the other hand, those teachers who want to counteract the dogmatism of the textbooks and convey some understanding of science as an activity that cannot be divorced from metaphysical or esthetic considerations may find some stimulation in the new history of science." No doubt about the mind and heart choice of this talented scientist and historian of science awarded in 2009 with the Abraham Pais Prize for the History of Physics. There is a growing literature on the history of this controversy. In addition to the works already cited, the interested reader may consult Bromberg (2008), Jacobsen (2012), Kaiser (2011), and Yeang (2011). We also highlight the English translation of most of the original papers in the history of this debate in Wheeler and Zurek (1983).

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Chapter 8
Teaching Energy Informed by the History and Epistemology of the Concept with Implications for Teacher Education

Manuel Bächtold and Muriel Guedj

8.1 Introduction

What can Epistemology and the History of Science and Technology (EHST hereafter) contribute to the field of teaching energy? Is it enough simply to evoke them as a way of broadening the learning after teaching the concept, that is, once students have mastered it, in order to offer them a few historical reference points and to spark off philosophical debate on the subject? That is not our point of view. On the contrary, we think that EHST could play a fundamental role in teaching energy, especially in regard to teacher training. Beynon wrote in 1990: 'I have no doubt at all that the problem of teaching energy will remain insoluble until teachers, themselves, have a clear understanding of the concept of energy' (1990, p. 316). We share this point of view. Indeed, for students to successfully understand and correctly apply the concept, it seems essential that their teachers themselves first master it, which is far from given. The highly abstract nature of the concept of energy (which is inseparable from the principle of energy conservation), its many possible forms (e.g. kinetic energy, thermal energy, nuclear energy), the distortions of meaning to which it is subject in everyday use (e.g. saying that energy can be 'produced' and 'consumed') all make it difficult to define the concept.

As we will try to demonstrate in this article, EHST provides the keys to understanding what energy is and, in particular, to at least begin to answer these three questions:

- 'What is the origin of the concept of energy?'
- 'What is energy?'
- 'What purpose does the concept of energy serve?'

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This is why our strategy consists of developing a training programme for teaching energy based on EHST. We start by discussing how teaching energy is covered throughout schooling (in the case of France), the learning difficulties associated with the concept and the main strategies presented in science education literature to teach the concept (Sect. 8.2). Then we outline our methodology and our two lines of research:

(i) EHST as part of teacher training for teaching energy
(ii) EHST as a means of rethinking how energy is taught (Sect. 8.3)

In the context of the first line of research, we present a framework for teacher training on the concept of energy based on EHST (Sect. 8.4). The second line of research will be addressed in a future article.

8.2 Teaching Energy: A Brief Overview of the Current Situation

8.2.1 Institutional Expectations and Teaching Energy: The Case of France

Energy appears as a concept across physical science programmes from primary through secondary school. Its progressive introduction throughout primary and secondary education has two main strands: the scientific approach to the concept and its implication in current social issues. Generally speaking, the emphasis is on a qualitative approach that prioritises the nature, role and properties of a concept that, although part of daily life, remains difficult to tackle.

In primary school (MEN 2008a), this qualitative approach is based on an introduction that aims to present energy via questions related to using and saving energy. In the further learning and consolidation stage, this does not involve introducing the scientific concept, but rather increasing pupils' awareness of the diverse situations that require a source of energy (using everyday vocabulary), identifying the principal sources of energy and distinguishing those that are renewable from those that are not. In addition, the concept of thermal insulators and conductors is first introduced, with the home providing a good illustration of this approach. The main goal of this initial contact with the concept of energy, which provides the opportunity for projects on the Industrial Revolution introduced in the history programme of the further learning stage, is to contribute to the education of the student as a future citizen.

This same goal also pertains to the educational programme at *collège* (the first stage of secondary school, age 10–14), which equally stresses a qualitative approach to energy; however, at this stage, the scientific concept is introduced and a definition given. The concept of energy, used as an example in the 'unity and diversity' theme that underlies the college (MEN 2008b) programme, is at the heart of the curriculum. It is presented as an essential concept in core knowledge and skills and is treated as a subject that provides a focal point.

The two main strands mentioned above are fully formulated at this stage. The definition is formulated as follows: 'energy is the capacity of a system to produce an effect' – it can be transformed and conserved. This first scientific approach to the concept proves necessary in order to introduce in a logical way a wide range of events that bring energy into play (e.g. day-to-day use of electric circuits, heat exchange, analysis of how living organisms function) and also constitutes essential knowledge for future citizens who need to be aware of the issues around energy that are central to debates in modern society.

In continuity with *collège*, the first year of *lycée* (high school, i.e. the second stage of secondary school, age 15–18) (MEN 2010a) calls for scientific learning and citizenship that will aid all students to succeed, while in the scientific stream of the two final years of *lycée* (MEN 2010b, 2011), the approach concerns vocational preparation to allow students to work towards careers in science. The emphasis is on acquiring skills in the discipline, encouraging interest in the sciences and making connections between science and society.

The final year of the scientific stream in *lycée* is structured around three axes: 'observe, understand,ct'. The purpose of these points of access to the scientific approach is to illustrate its main steps, giving a central role to the concept of energy, which is a sort of unifying theme throughout the 2 years of the course. In this way, the axis 'understand', dedicated to laws and models, presents energy as a common denominator of all basic interactions and the principle of conservation as an explanatory and predictive tool that allows awareness of the evolution of systems (second year of *lycée*). In addition, the study of the transfer of energy at different scales allows the introduction of the basic concept of thermodynamics (internal energy, thermal transfer, work, heat capacity) and a discussion of the irreversibility of phenomena and the causes of dissipation associated with these transfers (final year of *lycée*). This approach underlines the universality of the laws of physics, for which energy is presented as a unifying principle.

In this initial introduction, which highlights the nature, role and properties of the principle of conservation, the educational programme introduces the social and environmental issues related to energy. This includes knowledge about the variety of energy resources and saving energy, problems related to the production of electricity and the transport and storage of energy as well as the environmental impact of energy choices; all these subjects combine scientific knowledge and current issues in society. The axis 'act' sets out to develop this aspect.

The goal of the educational programme is the progressive construction of scientific knowledge and the development of skills suitable for initiation to experimental methods and practice. To help achieve this goal, the programme recommends making use of the history of science. Creating a historical perspective is structured around two axes: one concerning the nature of science and the other the scientific method. The aim, by emphasising the process of how knowledge is constructed, is to show that scientific truth has a particular status; it is the result of a codified process for which mistaken concepts and incorrect hypotheses are common. The history of science demonstrates that science is a social activity that is part and parcel of the culture in which it develops and that new ideas sometimes collide with tradition or dogmatism. These elements should be taken into account to contextualise science and '*mettre la science en culture*' (establish its place in a culture) (Lévy-Leblond 1973). This in turn should help to develop critical thinking, rethink the role of error and present the diversity of scientific methods, which cannot be reduced to a simple sequence of 'observation–modelling–verification', with the last having mainly a heuristic value.

8.2.2 A Difficult Concept to Grasp and Master

Although in general use, the concept of energy is abstract, difficult to define and subject to numerous recurrent conceptions noted by many writers.[1] The origins of these ideas are mainly found in everyday language, which contributes to the formation of imprecise or even mistaken concepts. The different meanings the term 'energy' and other related words take on in ordinary language are distant from or sometimes even incompatible with scientific concepts. In French, as well as in English, for example, it is common to associate the terms *energy* and *energetic* with strength and vigour. These words are often employed to describe a highly active person. Whereas in physics, the quantity of energy associated with a system may be very low. Moreover, energy may be in a form that is not even noticeable (this is the case for potential energy).[2]

In general discourse at least, people frequently speak about using, consuming, buying or selling energy, sometimes referring to fossil fuels themselves as 'energy'. This creates confusion between sources and forms of energy and presents a real obstacle in the acquisition of the principle of conservation.

Apart from language, daily experience can also prove to be a source of confusion, particularly for the youngest pupils. The ease with which it is possible to make an appliance function simply by plugging it into a socket implies that something can be obtained without anything being consumed. In the same way, obtaining electricity in hydroelectric or thermal power stations (especially nuclear power stations) takes on a magical character in which electricity seems to be stored.

The diversity of concepts related to energy makes it difficult to provide an exhaustive overview. Thus, we have chosen to mention only those, often cited by writers, which seem to be the most recurrent. Watts (1983) groups these according to seven categories:

- The anthropocentric conception, in which energy is associated with what is living.

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[1] See Solomon (1982, 1983, 1985), Watts (1983), Gilbert and Watts (1983), Duit (1984), Driver and Warrington (1985), Agabra (1985, 1986), Gilbert and Pope (1986), Trellu and Toussaint (1986), Trumper (1993), Ballini et al. (1997), and Bruguière et al. (2002).

[2] Fact sheet for Cycle 2 (basic learning in first years of primary school) and Cycle 3 (further learning in last years of primary school) (MEN 2002, p. 29)

- The conception of energy as a causal agent, in which energy is perceived as the cause of an event, as that which makes something happen. In this scenario, in which energy can be stored, the movement of a falling stone or a thrown ball is explained by the presence of potential and kinetic energy, respectively.
- The conception of energy as a product deriving from a process, a product that rapidly disappears and is not conserved.

To these three ideas, identified by Trumper (1990) as the most frequent, Watts adds the following four concepts. Energy can be perceived as an 'element' that lies dormant in certain objects and is released by a trigger. When energy is systematically associated with movement, Watts refers to the concept of 'activity' energy. This can be 'combustible' energy, where energy is equated to its source (oil, coal, natural gas and petrol are seen as energy), or 'fluid' energy, where energy is equated to a fluid that can be exchanged and transported. When this idea of energy as a fluid, i.e. as something 'quasi-material', is taken as an analogy only, it may be a fruitful tool for initially grasping the concept and the principle of its conservation (Duit 1987; see also below). However, the danger of making use of it in physics education is that students may take it literally and thereby endorse a non-scientific conception that is very hard to overcome (Warren 1982).

In the same vein, Robardet and Guillaud (1995) synthesise the work of other writers to summarise the most common conceptions, grouping these in three broad categories: energy as life (anthropocentric conception), energy as source (i.e. as cause of phenomena), and energy as product (i.e. as consequence of phenomena). This overview highlights the fact that energy is more noticeable when the effect produced is visible and even more so when the effect has a practical aspect or is associated with comfort. Thus, potential energy is little recognised by students (this point will be dealt with in Sect. 8.4.2).

These different conceptions result in several frequent and persistent errors, even after traditional learning (Trumper 1990). Without listing them all, we can cite, for example, the substantialisation of energy, confusion between the form and mode of transfer of energy; between force, speed and energy; and between heat, temperature and internal energy.

8.2.3 The Main Teaching Strategies

While educational programmes from primary to secondary school grant an increasingly large place to energy, the diversity, origin and consequences of mistaken ideas present a major obstacle to learning the scientific concept. Since the 1980s, the trickiness of teaching the concept has led certain educators to seek ways to facilitate its acquisition by taking into account related preconceptions. Generally speaking, traditional teaching is judged dogmatic and abstract (Lemeignan and Weil-Barais 1993), reducing the concept to a group of systematic technical procedures stripped of physical meaning.

The main teaching strategies are based on taking into account students' preconceptions during the application of the principle of conservation of energy. Thus, Trumper (1990, 1991, 1993), in the context of a constructivist approach, leads students to identify any conflicts between their own ideas and the properties required to establish the principle of conservation.

In the same spirit, the work of Agabra (1986) as well as Trellu and Toussaint (1986) promotes the concept of 'objective–obstacle' defined by Martinand, who suggests linking educational objectives with students' ideas, making the obstacles associated with the various preconceptions explicit and in each case indicating a specific way to surmount them.

Also in the constructivist framework, the work of Lemeignan and Weil-Barais (1993), extended by Robardet and Guillaud (1995), aims at constructing the concept of energy and its conservation by encouraging conceptualisation and only subsequently introducing classical formalism. The objective is to define, step by step, the semantic relationships that connect each object in the system studied with the next (e.g. an alternator powers a lamp in an overall system). By progressively establishing the semantic relationships, the energy exchanges that take place in the studied system can be defined.

Another teaching strategy consists of introducing energy as a 'quasi-material' substance. The supporters of this approach, which is in line with students' ideas of energy, justify their choice in pointing out the eminently abstract character of energy. Based on this idea, Duit (1987) and Millar (2005) suggest examining the different types of energy in a qualitative manner before tackling a quantitative, mathematical approach. This is a controversial choice of strategy, whose opponents underline the risk of perpetuating an entrenched false idea (Warren 1982).

Finally, writers agree on the terminological pitfalls, due in large part to everyday language – the meanings and uses of the term 'energy' vary considerably between informal and scientific contexts. Solomon (1985), Chisholm (1992) and Bruguière and colleagues (2002) argue that this problem could be mitigated by simplifying the vocabulary.

To this brief outline, it is fitting to add the work of Koliopoulos and Ravanis (1998), who group the various teaching strategies according to three categories. Their approach differs from those described previously as their classification is based on collected curricula from various countries and not directly on research results. This categorisation thus includes the aims of institutions and the issues that they consider important. So curricula qualified as 'traditional', 'innovative' and 'constructivist' are representative of these orientations.

The traditional curriculum corresponds to a classical mode of exposition in which energy, generally introduced as a concept derived from work, does not have a status in its own right. As a consequence, each field of study in physics requires a specific presentation of the concept, reflecting its many meanings.

The curriculum described as 'innovative' is based on ideas influential in the 1960s that promote the concept of energy by giving it a structural character and granting it a central place in the educational programme. This approach also introduces a social dimension to the learning of the concept.

The constructivist curriculum takes into account the current research orientations presented above. It is characterised notably by the construction of models of the energy chain and draws on students' prior conceptions.

In addition to the strategies outlined above, some writers suggest marshalling the history and philosophy of science in order to facilitate teaching energy. For the most part, the proposals revolve around aligning the difficulties confronted by scientists in the context of the emergence of the concept and students' ideas about energy. This is the case of Trellu and Toussaint (1986), who compare teaching centred on the conservation or transfer of energy; of Agabra (1986), who returns to the various models of heat; and of Duit (1987), who proposes that students could follow the same train of thought as certain nineteenth-century scientists; that is, start from a quasi-material conception of energy (see Sect. 8.4.2).

In contrast, Coelho (2009) draws from the work of Mayer and Joule to propose teaching centred on the notion of equivalence (e.g. heat and work), excluding the question of substantiality, which he supports is a source of confusion (see Sect. 8.4.2).

Generally speaking, the main aim of these proposals is to introduce elements of the history and philosophy of science in order to compare the difficulties of students to those confronted by scientists in the nineteenth century. History is employed here as a useful didactic tool, but little place is given to the cultural and scientific context.

8.3 Methodology for Designing a Teacher Training Programme for Teaching Energy

8.3.1 A New Strategy: Starting with Teacher Training

Although the range of strategies for teaching energy indicates its interest and these strategies contain innovative ideas, none has really managed to impose itself over the others. Teaching energy is considered complex and fragmented. This fragmentation is a result of the lack of connection between the fields of study concerned, which tends to obscure the principal properties of energy and precludes an understanding of the role of the principle of conservation. There seem to be as many meanings of the term *energy* as there are uses and fields of study.

In fact, teachers themselves feel ill-prepared when they have to take on this subject. This is notably referred to in the study mentioned above (Koliopoulos and Ravanis 1998), which aims to identify how experienced teachers teach the concept of energy. While this study shows that the majority of teachers choose traditional teaching methods, it indicates that strategies similar to those described as innovative and constructivist are also used. The latter two strategies are motivated, respectively, by the desire to underline the role of energy, in particular its unifying character, and by the necessity of taking into account students' prior ideas. However, some of the teachers who opt for an innovative approach in fact focus mainly on mechanical phenomena and eventually come back to a traditional approach that introduces energy by deriving it from work, while teachers opting more for a constructivist approach consider themselves poorly armed for incorporating students' conceptions in their teaching.

Furthermore, teachers themselves are not without mistaken conceptions concerning energy, especially in the case of primary school teachers (see, e.g. Summers and Kruger 1992; Trumper et al. 2000). Regarding secondary school teachers or students with science training, Pintó and colleagues (2004) and Méheut and colleagues (2004) highlight confusions regarding irreversibility and real phenomena, cyclical processes and reversibility as well as difficulty in conceptualising the dissipation of energy in the context of its conservation (thus, energy dissipation and conservation seem contradictory).

These various factors regarding teachers' ideas about energy and how it is learned prompt us to delve more deeply into what acts as an obstacle to implementing effective teaching and bring our attention to how teachers themselves are trained. It seems indispensable for teachers to be sufficiently at ease with the concepts to be able to undertake a critical analysis of their teaching practice and to rethink how energy is taught.

Clarifying the concept seems an essential first step to dispel any ambiguities related to the definitions of terms and the properties of the various concepts brought up. The concept of energy is complex, abstract and polymorphous, and the principle of conservation that characterises it is a unifying principle, a 'super law'[3] that structures physics. Explaining the properties and role of the principle leads back to the context of the emergence of the latter in the nineteenth century, to theoretical problems (questions relating to the dissipation of energy and the nature of heat), to experimental situations (the issue of increasing the profitability of machines), to mathematical formalism (the analytic expression of heat required to express the outcome during a Carnot cycle of operations) as well as to the philosophical context, the period being the subject of many debates regarding the founding concepts of physics (Freuler 1995).

This clarification of the concepts should allow the subsequent construction of teaching that highlights the fundamental characteristics of the principle of conservation of energy, defines the concepts related to energy and takes into account, with appropriate vocabulary, the social orientations given by official educational guidelines.

In this context, EHST seems to us an effective and fertile field for elucidating the concept of energy and rethinking how it is taught (on this point, see also Bächtold and Guedj 2012).

8.3.2 EHST in Teacher Training: The Case of France

The role of EHST in teacher training has long interested those who promote a full and authentic science education. In France, in 1902, the institutionalisation of science teaching in secondary school was coupled with the university-level

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[3] This expression comes from Michel Hulin (1992) in his book entitled *Le mirage et la nécessité: pour une redéfinition de la formation scientifique de base*.

development of a general history of science aimed mainly at teachers. Later, in the 1970s, reforms stressed the necessity of transmitting historical knowledge in university programmes as well as in teacher training, including for primary teachers. In mathematics, these reflections were largely the realm of the newly created IREMs.[4] The SFHST,[5] since its creation in 1980, has supported EHST initiatives, which have continued to develop.

In what she describes as the 'long march' of EHST education, Fauque (2006) points out that in the 1980s, the concerns of French researchers on the subject were shared abroad. She notes the reach of Bevilacqua's work at the University of Pavia, leading to numerous educational publications that introduced elements from the history of science based on local archives (primary sources and scientific instruments) into science teaching. In 1983, under the impetus of Bevilacqua and Kennedy,[6] the first international conference was held in Pavia. Many others would follow: at the *Deutsches Museum* in Munich, at *La Cité des Sciences et de l'Industrie* in Paris and in Cambridge, to mention only the first three conferences.

This impetus also resulted in the production of literature by specialist organisations, which allowed teaching proposals to be supplemented by reports on the results of experiments. This was notably the case of the French Physicists' Union (*Union des Physiciens en France*) and the Association for Physics Education (*Associazione per l'insegnamento della fisica*) in Italy. The work of Shortland and Warwick (1989) in Britain was in the same spirit, with their publication (under the aegis of the British Society for the History of Science) of *Teaching the History of Science*, as was that of Matthews[7] with the creation of the journal *Science & Education*, as well as another work dedicated to this question (Matthews 1994/2014). Although far from comprehensive, this overview testifies to a shared wish to integrate EHST in science education.

Likewise, in France, the place given to EHST in school programmes increased, with its inclusion in core knowledge and skills,[8] in recruitment examinations as well as in the guidelines for teachers' skills,[9] all aspects of the same approach.

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[4] *Instituts de Recherche sur l'Enseignement des Mathématiques* (Research Institutes for Teaching Mathematics).

[5] *Société Française d'Histoire des Sciences et des Techniques* (French Society of the History of Science and Technology).

[6] P. J. Kennedy was professor at the University of Edinburgh.

[7] University of New South Wales, Sydney.

[8] The core skills are those considered essential to master by the end of compulsory education. The section dedicated to scientific and technological knowledge emphasises: 'The presentation of the history and the development of concepts, drawing from resources in all the disciplines concerned, is an opportunity to tackle complexity: the historical perspective contributes to providing a coherent vision of science and technology as well as their joint development' (pp. 12–13).

[9] Secondary school teachers should be able to 'situate their discipline(s) within its history, its epistemological issues, its didactic problems and the debates that affect it'. *Framework of reference for teachers' professional skills* (extract from the decree of 19 December 2006 containing guidelines for teacher training, MEN 2007).

In 1999, Lecourt (1999) submitted his report concerning the role of teaching the history and philosophy of science in French universities in which discussed the many factors related to its instruction. Noting the disaffection with studying science, he stressed the necessity of breaking away from the highly technical nature to which science study is often reduced, emphasising the need to give meaning to scientific knowledge and situating it within other types of knowledge – humanising it. Lecourt denounced the harmful effects caused by a lack of EHST education in the curriculum, leading students to adopt an implicit philosophy close to scientism. Several studies reveal the frequent adoption of scientism, whether by students (Désautels and Larochelle 1989) or teachers (Abd-El-Khalik 2001). In the same vein is Paty's (Paty 2000–2001, pp. 56–57) assertion that EHST is essential for discussing the value of scientific truth, while the discourse in society tends to equate revealed truth and scientific truth. Paty reminds us that although scientific truth is relative in the sense that it is incomplete and prone to modification, it has a specific status resulting from a mode of attribution of proof that is clearly identified.

A central element in reflecting on the sciences, in terms of content, methods and links with other fields of knowledge, EHST is essential for reintegrating science in culture. 'Putting science (back) into culture', in the words of Lévy-Leblond (2007), is not a question of creating effective means of transmitting scientific results to the wider public; it is rather about rethinking the sciences, their practice and their methods, in order to produce new, innovative knowledge. Taking up this challenge involves developing critical thinking, too often neglected according to this writer, and prompts consideration regarding the training of scientists. Although referring to the latter, the statement that follows could equally serve as an explanation for the guidelines for teacher training mentioned above:

> Can we continue to train professional scientists without giving them the least element of comprehension of the history of science – concerning their discipline first of all – and of the philosophy, sociology and economy of science? The tasks they now face in practicing their occupation, and the social responsibilities that they can no longer ignore, require them to have a broad conception of scientific work. How can we believe any longer that science is different in this regard than art, philosophy or literature, fields of human activity that no one would imagine teaching independently from their history? (Paty 2000–2001, pp. 13–14)

Training future scientists and educating the citizens of tomorrow necessitate bringing together diverse skills, which we should remember are already widely present in school programmes. Martinand (1993, p. 98) comes to the same conclusion when he emphasises shortcomings in future teachers uninformed about the practices and culture of science: 'The "mission" of the history and the epistemology of science is to enrich research and reflection about its practice, evolution and foundation, without an immediate didactic aim.'

Lastly, in a more specific way, EHST education supports the teaching of scientific disciplines through an epistemological examination of problems, concepts and theories. In the study previously mentioned, Martinand points out that thanks to its critical and prospective function, EHST allows encountered problems to be clarified and teaching content to be questioned in order to better understand its integration in school programmes. Epistemology 'at the service of education' should supplement the orientations developed above.

8.3.3 The Proposed Approach

In the context of the study of energy, the aforementioned approaches lead to a re-examination of the foundations of the concept and its emergence in order to understand its role, properties and functions. This should allow the concept, its principle of conservation and its related concepts (in particular, work, force and heat) to be clarified. All of these steps are essential for teachers. The development of this approach, which enlists the acquisition of 'scientific culture', is a first line of research. Using EHST at the service of teaching energy will be a second, future line of research.

8.3.3.1 EHST in Teacher Training for Teaching Energy

The rest of this article (see Sect. 8.4) will focus on the first line of research. How should teacher training based on EHST be designed to help teachers acquire scientific culture around energy? To develop the beginning of a response to this, we have drawn from many existing works, not only in the field of EHST,[10] but also in science education.[11] Based on these works, we have created a general framework for teacher training on energy, which aims to include all the aspects of the concept and to introduce them according to the most logical progression of ideas possible. We have striven to avoid the pitfall of drowning teachers in an overly complex and detailed history and epistemology of the concept of energy. In particular, the cultural and scientific contexts are not examined in detail, as they would be in a historical study.[12] The aim is to make the use of history and epistemology functional and accessible to teachers. Furthermore, to be both relevant and enlightening, such a historical and

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[10] Several historical and epistemological studies on energy were published by scientists and/or philosophers of science at the end of the nineteenth century and the beginning of the twentieth century (e.g. Mach, Planck, Poincaré, Meyerson and Cassirer). Later, Kuhn's (1959) article encouraged science historians to carry out new investigations on the emergence of the concept in the nineteenth century (e.g. Elkana 1974; Truesdell 1980; Hiebert 1981; Smith and Wise 1989; Caneva 1993; Smith 1998; Ghesquier-Pourcin et al. 2010). It should be noted that the history of the concept of energy over the course of the twentieth century, with the advent of the theory of relativity (special and general relativity) and of quantum mechanics, as well as the importation of the concept in many other fields (chemistry, biology, economics, arts, etc.), has not yet been well studied.

[11] See in particular the literature indicated in Sect. 8.2.

[12] For further information on these aspects, see the references in the previous footnote.

epistemological introduction must be centred on physical content. Hence, we suggest the teacher training programme could be organised around three points[13]:

What is the origin of the concept of energy?
The investigation of this question aims to challenge the idea that the concept of energy, with the meaning attributed to it today, was always available for scientists. The goal of teacher training here is not only to make teachers aware that the current accepted scientific understanding of the concept only stabilised in physics in the middle of the nineteenth century but also to supply teachers with information to help them understand why it stabilised at this time and how the process of this stabilisation came about.

What is energy?
So that teachers can fully grasp the meaning of the concept of energy, teacher training should clarify all characteristics of the concept (i.e. energy is a quantity associated with a system, it can take different forms, it can be transformed and transferred; see Sect. 8.4), rather than reducing it to the principle of conservation of energy. When dealing with this question, it also seems appropriate to discuss incorrect ideas that can be obstacles to learning the concept.

What purpose does the concept of energy serve?
So that teachers understand and can explain to students the omnipresence of the concept of energy in the curriculum, teacher training should clarify the different functions that this concept allows to be performed in scientific work.

This framework, which will be elaborated upon in Sect. 8.4, makes up the first step of the creation of a teacher training programme, which can then be enriched with examples of possible course outlines and teaching sessions on energy (see the second line of research presented below) and added to allowing for constraints on the ground (type of teacher, available time, equipment and resources, etc.). We then plan an experimentation phase for the training programme in order to assess its impact and attain an empirical response that will enable us to improve it.

8.3.3.2 Using EHST to Rethink the Teaching of Energy

The second line of research mentioned above, that is, EHST at the service of teaching energy, is the subject of a study currently in progress that will be expounded in an upcoming article. Our first hypothesis, which is the basis of this study, is that a teacher training programme on energy based on EHST should profoundly redefine

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[13] The inspiration here is from Papadouris and Constantinou (2011, p. 966), who ‘take the perspective that any attempt to promote students’ understanding about energy should primarily address the question ‘What is energy and why is it useful in science?’. However, we diverge from these writers’ approach on several points: we maintain that it is pertinent to include the question of the origin of the concept of energy; we suggest approaching the three questions drawing on EHST; and, lastly, we do not provide the same answers to the questions posed.

the way in which teachers themselves envisage teaching about energy. More specifically, this teacher training programme should lead teachers towards:

- A new insight into educational programmes (a better global overview as well as an understanding of the relationship between the different sections of these programmes)
- A reflection on their own ideas about energy and its related concepts (e.g. work, heat)
- A new way of taking into account students' prior conceptions
- A review of practices in teaching energy (in terms of the coherence of planned teaching sessions, the organisation of the content, the method used to develop knowledge and, in particular, the relationship between theory and experimentation and the formulation of problems)

The objective of this research study is to come up with concrete proposals for course outlines and teaching sessions on energy making use of EHST. In these proposals, we intend to supply examples of teaching about energy that do not call on the history of science as an optional extra (the 'add-on' approach; see Matthews 1994, p. 70), but rather place it, and epistemology, at the centre of instruction. Our second hypothesis, which remains to be tested, is that such teaching should allow the many difficulties related to the acquisition of the concept of energy to be more easily overcome (see Sect. 8.2).

8.4 Framework for Teacher Training on Energy Based on the History and Epistemology of the Concept

8.4.1 What Is the Origin of the Concept of Energy?

The absence of historical perspective encourages the illusion of the immutable nature of scientific concepts and theories, as if these have always been available for scientists and cannot be challenged or revised in the future. The same is true for the concept of energy. The fact that today it is omnipresent in physics and the other sciences makes it difficult to imagine that only 200 years ago it was not yet fully part of the armoury of physics. So that teachers understand the concept of energy and can grasp its meaning and utility (see Sects. 8.4.2 and 8.4.3), it seems crucial that beforehand they are clear about its origin: where does the concept of energy come from – or, in other words, why and how was this concept introduced in physics?

The first fundamental point that should be emphasised is:

> In its accepted scientific meaning, the concept of energy is inseparable from the principle of its conservation which was established in the middle of the nineteenth century.

This point is expressed by Balibar (2010, p. 403) in this way: 'The concept of energy only became a physics concept from the moment it was irreversibly established that a law of energy conservation exists'.

This initial point guides the rest of our discussion, since it leads us to replace the question ‘What is the origin of the concept of energy?’ with ‘What is the origin of *the principle of conservation* of energy?’ This latter question can be approached from two perspectives: one centred on the people who participated in the emergence of the principle and the second centred on the epistemic factors that played a role in this emergence, namely, experimentation and reasoning. These two perspectives should be combined to avoid the risk of a truncated answer.

Concerning the first perspective, the history of energy is particularly instructive for teachers, whose historical idea of science often consists merely of a succession of ‘discoveries’ made by isolated geniuses – discoveries that are considered independently of context (scientific, technological, philosophical, etc.) (see, e.g. Gil-Pérez et al. 2002, pp. 563–564). The case of the principle of conservation of energy is illustrative of this. The historical study of its emergence is an opportunity to challenge and enrich the vision that teachers have about the history of science.

> The principle of conservation of energy emerged in the middle of the nineteenth century following different research projects led by several scientists (among others, by Mayer, Joule and Helmholtz) influenced by their scientific, technological, philosophical and religious context.

Three points merit emphasising to teachers. Firstly, the principle was not discovered by an isolated genius. This point was underlined by Kuhn (1959), who lists no less than 12 scientists that ‘simultaneously’ participated in the ‘discovery’ of the principle.[14]

Secondly, the term *emergence* is more relevant than discovery, because the latter suggests an image that does not comply with the history of the principle – as if it pre-existed all scientific research and was suddenly revealed. This misleading image obscures the work of *construction* carried out by scientists. In fact, energy with all its properties (see Sect. 8.4.2) is not directly observed in nature. Before scientists could accept energy as a physical reality, they first had to construct and stabilise the concept. This construction was progressive, not the result of one action. During the seventeenth and eighteenth centuries, the precursors of the energy conservation principle (e.g. Leibniz, Huygens, Jean Bernoulli, Lagrange) prepared the groundwork for this construction in the field of mechanics by forging and developing the concepts of *vis viva* or living force (the ancestor of kinetic energy) and *vis mortua* or dead force (the ancestor of potential energy) and by establishing as a theorem, in the middle of the century, the conservation of these two quantities in idealised and isolated mechanical systems – this theorem being identified a century later as a particular case in the energy conservation principle (see Hiebert 1981, pp. 5 and 95). It should also be pointed out that in the middle of the nineteenth century, scientists that contributed to the emergence of the principle ‘were not saying the same things’ (Kuhn 1959, p. 322) or, as Elkana notes (1974, p. 178), they came up with solutions

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[14] In the order of occurrence in Kuhn’s text: Mayer, Joule, Colding, Helmholtz, Carnot, Séguin, Holtzmann, Hirn, Mohr, Grove, Faraday and Liebig. This list is not meant to be exhaustive, and other scientists could be added, such as W. Thomson (Lord Kelvin) and Rankine, whose contributions came later but were no less conclusive.

to ‘different problems’. It was only progressively, over the course of the 1850s, that the different quantities of living force, work, heat, etc. were identified as examples of the same quantity – that is, energy – and that the new ideas defended by these scientists were recognised as equivalents, bringing to light the conservation of this quantity (see Elkana 1974, p. 10, Guedj 2010, p. 118).

Thirdly, the emergence of the principle cannot easily be understood independently of its scientific, technological, philosophical and religious context. In terms of the scientific context, the decisive elements were of both a theoretical and experimental nature. As we mentioned above, the principle of conservation of living force and dead force was established in the middle of the eighteenth century. However, this principle had limited impact and fell within the framework of nonconservative rational mechanics, which took into account the existence of an observed loss of living force during collisions. It was not until a new generation of engineers (Navier, Coriolis, etc.) proposed a molecular approach that rational mechanics would be transformed to conservative mechanics, in which the loss of living force is considered only apparent. This was an essential step towards the construction of a general principle of energy conservation (on this point, see Darrigol 2001). To these concerns related to mechanics must be added those regarding heat. In the first half of the nineteenth century, the idea that living force could be converted into heat (today we refer to the conversion of kinetic energy into thermal energy) appeared. During this period, many other conversion processes were experimentally brought to light, establishing the relationships between different fields (heat science, mechanics, chemistry, electricity, magnetism, animal physiology, etc.).

The technological context also had a major influence. The development of steam engines and electric machines played a significant role in the theoretical developments of the first part of the nineteenth century. For example, the scientific concept of work, essential in the formulation of the principle of energy conservation, was derived by scientists from accumulated experiments in the field of mechanical engineering (see Kuhn 1959; Elkana 1974, pp. 40–41; Vatin 2010).

Lastly, historians of science also accept the influence of the philosophical and religious context, although these are more complex to grasp. The metaphysical idea[15] of the equality of cause and effect, as formulated in particular by Leibniz, was shared by many of those involved in the emergence of the principle (e.g. Mayer, Helmholtz) and motivated them to search for a conserved physical quantity (see Mach 1987 [1883], pp. 474–475; Meyerson 1908, pp. 181–184; Kuhn 1959). Nor are religious considerations absent from scientific reasoning. Citing, for example, Joule:

> We might reason, *a priori*, that such absolute destruction of living force cannot possibly take place, because it is manifestly absurd to suppose that the powers with which God has endowed matter can be destroyed any more than they can be created by man’s agency. (Joule 1847)

This perspective centred on the participants involved contributes vital information about the origin of the principle of conservation of energy and situates it in its context. However, it also seems important to combine this perspective with one

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[15] By ‘metaphysical’, we mean an idea that precedes any scientific research.

centred on epistemic factors, namely, reasoning and experimentation, so that teachers have a full understanding of the nature of the principle. The question of the origin of the principle could be posed in the following terms: (i) Is the principle an empirical law (an a posteriori law) resulting from experimental investigation or (ii) is it a metaphysical principle (an a priori principle) established by reasoning?[16] Teachers are inclined to opt for option (i), in accordance with the inductivist 'naïve' conception of the scientific approach that they tend to spontaneously adopt.[17] However, the history of science reveals that neither of these alternatives 'conforms to the historical truth', as Meyerson states (1908, p. 175). The response is found midway between them:

> The principle of conservation of energy is the result of a mutual adjustment between an a priori question posed by scientists searching for a quantity conserved during all transformations and the experimentation that allowed what this quantity is to be determined.

How can this interrelationship between the empirical aspect and the a priori aspect in the emergence of the principle be illustrated in teacher training? Taking our inspiration from Meyerson (1908, pp. 175–190), we suggest first examining option (i) in light of Joule's experiments and then option (ii) in light of the principle of the equality of cause and effect.

In an article from 1847, Joule claimed to have established on the basis of several experiments that living force can be converted into heat and that, inversely, heat can be converted into living force,[18] without anything being lost during the two conversions:

> Experiment […] has shown that, wherever living force is *apparently* destroyed, an equivalent is produced which in process of time may be reconverted into living force. This equivalent is *heat*. […] In these conversions nothing is ever lost. (Joule 1847, pp. 270–271)

This idea of mutual convertibility without loss is not strictly equivalent to the principle of conservation of energy, but is an important step towards it: it was yet to be accepted that living force and heat were two examples of the same quantity – energy – or to generalise the specific case of mutual convertibility without loss between living force and heat to all possible conversions between different forms of energy. Two of Joule's experiments could be presented in teacher training to illustrate mutual convertibility: the first demonstrating the conversion of living force to heat (the famous experiment during which a falling mass rotates paddles in a liquid and through the effect of friction causes the

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[16] It should be noted that advances in the mathematical sophistication of the laws of physics were a necessary precondition for the emergence of the principle.

[17] See, for example, Robardet and Guillaud (1995, Chap. 3), Gil-Pérez et al. (2002, p. 563), Johsua and Dupin (2003, pp. 215–217) and Cariou (2011, pp. 84–86). A survey of teachers would be worth carrying out to corroborate this hypothesis regarding their choice of option (i).

[18] In accordance with current terminology, one should speak of the mutual convertibility between kinetic energy and thermal energy (a form of energy, as distinct from heat, or 'thermal transfer', which is a mode of energy transfer).

temperature of the liquid to rise) and the second demonstrating the inverse conversion (the experiment on the expansion of heated air).

These two experiments carried out by Joule indeed demonstrate the mutual convertibility between living force and heat. The problem is that they do not prove the absence of loss during each conversion. To do this, the first experiment would need to establish that a given quantity A of living force always results in exactly the same quantity B of heat, while the second experiment would need to establish that quantity B of heat always results in exactly the same quantity A of living force. Yet for the first experiment, Joule's initial results in the 1840s were marred by significant dispersion and were obtained on a temperature scale too small to be accepted. This explains why, as Truesdell points out (1980, p. 180), Joule's contemporaries, such as W. Thomson, Helmholtz and Rankine, 'were reluctant to accept his early results'. In the second experiment, the problem was even more serious: as W. Thomson (1852) indicated, 'full restoration' of heat in living force (Thomson speaks of 'mechanical energy') is in practice 'impossible' because of the phenomenon of the 'dissipation' of energy. For this reason, contrary to what he asserts in his writings, Joule was not in a position to be able to experimentally establish the mutual convertibility *without loss* between living force and heat. This examination of the case of Joule suggests the dismissal of option (i): historically, the principle of energy conservation was not drawn directly from experiments.

Turning to option (ii), according to which the principle was established by a priori reasoning, several scientists that contributed to the emergence of the principle (e.g. Mayer, Helmholtz) presented the principle of energy conservation as a consequence of the principle of the equality of cause and effect. For example, here is what Mayer wrote in 1842:

> Forces are causes: accordingly, we may in relation to them make full application of the principle: *Causa aquet effectum*. […] In a chain of causes and effects, a term or a part of a term can never […] become equal to nothing. This first property of all causes we call their indestructibility. […] Forces are therefore indestructible, convertible, imponderable objects. (Mayer 1842, quoted and translated by Truesdell 1980, p. 155)[19]

The principle of equality of cause and effect can certainly be interpreted in terms of the conservation of a quantity in a relationship of cause and effect (a quantity that is instantiated first in the cause and then in the effect), but does not in any way determine what this conserved quantity is. In fact, different options have been favoured by scientists through history: in the seventeenth century, Descartes thought it was the 'quantity of motion' (the ancestor of momentum)[20]; soon after, Leibniz suggested

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[19] As stressed by Caneva (1993, pp. 25–27, 46 and 323), Mayer came to this idea of the conservation of 'force' (an ancestor of energy) by making an analogy with the conservation of matter (the latter being still implicit in physics and chemistry at the time of Mayer and made explicit by him). This 'guiding analogy' can also be considered as an a priori reasoning towards the principle of conservation of energy.

[20] Unlike momentum as it is defined today, Descartes' 'quantity of motion' (*quantité de mouvement*) was a scalar and not a vector quantity. See Descartes (1996 [1644]).

it was living force[21]; throughout the eighteenth century, scientists preferred Leibniz's proposition; from the second half of the eighteenth century, Lavoisier put forward the caloric theory (the caloric being conceived as a conserved 'fluid' that is the 'cause of heat')[22]; it was finally in the middle of the nineteenth century that a new concept of energy, conceived as a more general quantity capable of taking the form of living force and of heat, was accepted as the conserved quantity. In other words, although scientists indeed had an a priori idea of the existence of a quantity conserved during any transformation, energy could not be identified as the quantity sought without the aid of experiments and, in particular, without the many conversions demonstrated in the first half of the nineteenth century.

One last point concerning the origin of the principle of conservation of energy warrants clarification for teachers so that they grasp its role in the theoretical structure of physics. It should be noted that it was first described as one of the two 'principles' of *thermodynamics* (as first formulated in the 1850s) before being considered as a principle of *physics* (i.e. of thermodynamics but also of other physics theories that developed later, such as electrodynamics, special and general relativity and quantum mechanics). Establishing the conservation of energy as a principle has two implications: (a) this proposition is asserted as true without requiring that it be demonstrated by other propositions, and (b) it acts as an axiom on which other propositions in physics are based.

Points (a) and (b) each give rise to the questions: 'What justifies that the proposition of the conservation of energy is asserted as true?' and 'Why adopt this proposition as an axiom of physics?' The history of energy that we have just outlined in broad strokes leads to an initial answer to the first question: although neither experiments nor reasoning allows conclusive proof of the truth of energy conservation, both offer elements that corroborate this conclusion. A second answer can be found in Cassirer's analysis (1929 [1972], p. 508) of the relationship between a principle and an experiment: it is legitimate to accept the 'validity' of a principle on the strength of the accordance of all the consequences that can be derived from experimentation. To the second question, a possible answer is the following: scientists choose the conservation of energy as an axiom of physics because of its functional character (see Sect. 8.4.3).

8.4.2 What Is Energy?

It is difficult to describe what energy is and to give it a definition that encompasses a consensus. For this reason, some scientists put forward the minimal definition that describes energy as a quantity that is conserved. Thus, Poincaré argues (1968 [1902], pp. 177–178): 'As we cannot give energy a general definition, the principle

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[21] On the controversy between Descartes and Leibniz on this point, see, e.g. Iltis (1971).

[22] See Lavoisier (1864 [1789]).

of conservation of energy simply means that there is *something* that remains constant.' Likewise, Feynman writes:

> There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. […] It is important to realize that in physics today, we have no knowledge of what energy *is*. (Feynman 1963, 4.1–4.2)

It is true that the principle of conservation of energy is the integral core of the concept of energy. It is also true that the concept of energy is very abstract: not only does it describe a quantity of which we have only very indirect experimental access through the intermediary of the measurement of other quantities (such as speed or temperature), but additionally, it does not refer to a particular type of phenomena (e.g. mechanical or thermal), but to all phenomena. This is why certain science education writers, such as Warren (1982, 1991), argue the concept should not be taught in primary school, but only when students have mastered the mathematical tools that allow them to apply the principle of conservation of energy.

We believe that teaching energy by defining it uniquely as a conserved quantity and limiting it to mathematical operations of the principle of its conservation is largely inadequate for understanding its meaning. Teacher training should explicitly identify, explain and relate all the characteristics of energy (we distinguish eight) that remain implicit in traditional teaching. It seems useful, at the same time, to point out the recurrent incorrect ideas of students and teachers – on the one hand, so that they grasp what energy is *not* and, on the other hand, so that they are aware of the stumbling blocks of learning the concept. History and epistemology of the concept of energy should be included in teacher training as these bring valuable perspective on its different characteristics. Below we set out the eight characteristics of energy and outline one possible way to approach them. The first is:

(1) Energy is a quantity associated with a system.

We suggest introducing this characteristic in a discussion of the substantialist conception of energy, which is the idea that is most recurrent and most ingrained in students' and teachers' minds and thus also the most difficult to overcome. The merit of the substantialist conception is that it allows us to think more easily about the conservation of energy. This is why, rather than dismissing this conception out of hand, one could imagine taking advantage of it. The history of science is here a source of inspiration. As Duit notes (1987, pp. 140–141), referring to Planck (1887), the analogy of the conservation of energy to the conservation of matter played an important role in the acceptation of the former. According to Duit, introducing students to the conception of energy as something 'quasi-material' allows this quantity to be presented as something more 'concrete' or 'tangible' and so aids in understanding it (see also Millar 2005). This proposal seems useful in the context of teacher training. However, it is important to stress to teachers, first, that this conception is an *analogy* and, second, its limitations.

The first limitation of the substantialist conception is in fact characteristic (1): energy is a physical quantity associated with a system; that is, it does not exist autonomously, independent of a system. Or as Bunge writes (2000, p. 459): 'All energy is the energy of something.' In order to avoid the erroneous conception that a system plays the role of a reservoir of energy (the 'depository model'; see Watts 1983), it should be emphasised, as by Millar (2005, p. 4), that energy is not *in* a system, i.e. it is not 'contained' or 'stored' by it, as can be gasoline in a tank, for instance. In physics, it is a question of the energy *of* a system, i.e. energy is a 'state quantity', a variable quantity determined by the state of the system and indicating the system's capacity to produce change (see characteristic 3).

The second limitation of the substantialist conception concerns the two components of mechanical energy that are characterised by a second level of relativity. Kinetic energy is relative to the frame of reference considered (because speed, which features in the expression of kinetic energy, is itself relative to the frame of reference). The potential energy is doubly relative: it depends on the presence and the position of other systems but also on the choice of the coordinate system used to determine its value.[23] This double relativity of potential energy was put forward by Hertz (1894), who noted that a quantity capable of assuming negative values would not be able to be interpreted as representing a substance.[24]

We should add that, in the framework of special relativity, this second limitation is generalised to the total energy of a system, which is relative to the frame of reference considered.

To sum up, comparing energy with matter appears to be a useful analogy favouring the acquisition of the principle of conservation of energy. Nevertheless, as is the case for any analogy, this quasi-material concept has some limitations: energy is not an autonomous substance and its value is not absolute. To avoid teachers taking this concept literally, it is essential to emphasise that it is only an analogy and explain its limitations.

The concept of 'system' used here may seem self-evident. However, as several science education writers have emphasised (Trellu and Toussaint 1986, pp. 68–69, Arons 1999, p. 1066, van Huis and van den Berg 1993), in order to understand the conservation principle and be able to unambiguously describe energy exchange, it is essential to clearly define what a system is and to specify the boundaries of the system for each situation considered. In particular, when defining a system, it is important to stress the distinction between the system, which is the object (or group of objects) that we want to describe, and its 'environment', with which it can interact, and thus exchange energy (see characteristics 6 and 7), and/or with which it can exchange matter.

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[23] Note that, in classical mechanics, potential energy depends only on the relative distances between the interacting bodies. Therefore, if all these interacting bodies are included in the system, the potential energy of this system no longer depends on the choice of the coordinate system.

[24] Hertz actually rejected potential energy, emphasising the role of the kinetic energy of hidden masses.

The second characteristic of energy is an extension of the first:

(2) Energy is a universal quantity: it is associated with all systems and all fields of science.

As Bunge writes (2000, p. 459): ‘Energy is the universal physical property.’ However, he restricts the field of application of this property to material objects only. Yet it is important to underline that energy is also a quantity associated with all electromagnetic radiation. In addition, this quantity has a universal character due to the fact that it applies to all fields of science: physics, chemistry, biology, geology, physiology, etc.[25]

When we express the universality of the quantity of energy in this way, it is important to draw attention to a possible inversion that should be avoided regarding the historical process. Scientists did not first identify energy in a particular branch of physics and then discover that this quantity was also associated with systems being studied in other branches of physics as well as in other scientific fields. On the contrary, it was the connection between the different branches of physics and other scientific fields (in particular, heat science, mechanics and physiology) that led to the emergence of the concept of energy (see Kuhn 1959). Its universality and its correlative function of unification (see Sect. 8.4.3) are the constituent features of the concept.

For us, this partly explains the abstract nature of the concept of energy: if it is abstract, this is notably because of its universal reach. Indeed, the concept must achieve a certain level of abstraction in order to subsume all forms of energy and be universal. In other words, it was through a process of abstraction based on concrete phenomena in each branch of physics and field of science that the concept of energy was formed.

Saying that energy is a quantity associated with a system is still a very limited characterisation of energy and does not enable it to be distinguished from other quantities. Certain science education writers (e.g. Warren 1982, 1991) argue that the energy of a system should be defined as its ‘capacity for doing work’, because this definition is necessary for thinking about the different forms of energy, as well as the conservation of energy. Other writers (e.g. Sexl 1981; Duit 1981; Trumper 1991) disagree with this definition as it is restricted to the field of mechanics; in other words, it suggests that the effects or changes a system is able to produce by virtue of its energy are merely mechanical (i.e. work). This criticism is understandable. But why not retain the definition of the energy of a system as its capacity to produce *change*? The main objection of Duit (1981, p. 293) is the following: ‘The ability to bring about changes can also justifiably be attributed to a number of other physical concepts (for example, force and torque).’ However, this objection is not admissible in our view. First, energy is a quantity that is the property of *one* system, while the quantities mentioned by Duit, such as force and

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[25] It should also be noted that energy is equally employed in the social sciences: economics, psychology, sociology, etc. However, the meaning of the concept of energy and the uses made of it are not necessarily the same as in the physical sciences.

torque, model the action of one system on another. Second, the changes produced by force or torque occur simultaneously with its application, while the changes a system can produce by virtue of its energy are only potential: that is, only energy describes the *capacity* of a system to produce change.

Even if slightly different definitions of energy may be available (namely, in terms of work or in terms of change), it is essential to provide teachers and students with this definition of the capacity to produce change. It not only aids in clarifying the physical meaning of the concept of energy and thus in distinguishing it from other physical quantities but is also necessary for thinking about characteristics (4)–(8) of energy. Taking our inspiration from several writers, such as Chisholm (1992), Bunge (2000), and Doménech and associates (2007), without following them exactly,[26] and in line with French *collège* programmes (see Sect. 8.2.1), we propose the following definition, which we identify as the third characteristic of energy:

(3) The energy of a system is its capacity to produce change (within the system or in other systems).

Now let us turn to the other characteristics of energy and show why this definition is necessary to understand them properly. The fourth characteristic can be expressed as:

(4) Energy can take different forms.

Here it is worth restating the possible inversion of the historical process as mentioned above, though expressed in slightly different terms. Scientists did not first discover energy as a well-defined quantity appearing in a particular form (e.g. kinetic energy) before searching for and discovering the other forms in which it can also appear (e.g. thermal energy, electric energy). They first defined distinct quantities representing distinct physical realities (e.g. living force, work, heat), before making the connections between them and conceiving of them as examples of the same quantity.

Only by defining the energy of a system as its capacity to produce change gives meaning to the idea that distinct quantities representing distinct physical realities are examples of the same quantity. In fact, the only point in common between these different quantities lies in their capacity to produce the same changes. For this reason, in our view, it is the equivalence of these quantities in terms of the capacity to produce the same changes that justifies considering them as different expressions of one and the same quantity – energy.

The following historical fact supports our argument: the identification in the 1850s of the different quantities of living force, work, heat, etc. as examples of energy

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[26] Chisholm (1992, p. 217) writes: 'Energy […] produces changes.' Bunge (2000, p. 458) identifies energy with 'changeability'. For us, these two definitions do not adequately elucidate the idea of capacity. Doménech et al. (2007, p. 51) define energy 'as the capacity to produce transformations'. We criticise this definition for the use of the term 'transformation' rather than 'change'. The latter term is more general than the former and, in particular, can include variation in the value of a quantity (such as temperature or speed), which is not usually described as a 'transformation'.

recognised as being the conserved quantity is concurrent with the introduction of the definition of energy as the 'capacity to effect changes' or 'capacity for performing work' (Rankine 1855, pp. 125 and 129).[27]

The adoption of this definition of the energy of a system as its capacity to produce change led to the reconsideration in a new light of the common conception of kinetic energy as 'actual energy' (to use Rankine's term, 1855), a form that would appear directly to us through the movement of a material system. Certainly, the speed v and mass m of a studied system determine its kinetic energy, and we have relatively direct experimental access to these quantities. Yet that which justifies considering the formula $½mv^2$ as the expression of *energy* is not the manifestation of the movement itself, but rather the potential effects of this movement, or in other words, the capacity of the system driven by this movement to produce change (e.g. the ascent of the system up a slope or the deformation of a second system following a collision). This is why we challenge the assertion of certain writers (see Agabra 1985, pp. 111–112) that the concept of potential energy is much less accessible than that of kinetic energy. Although learners may easily accept the statement that a material system in movement possesses 'kinetic energy', that does not mean that they have understood the meaning of the concept of energy. Unless they recognise potential energy as a possible form of energy in the same right as kinetic energy and this by virtue of their common capacity to produce change, it is not guaranteed that the term 'kinetic energy' means anything else to them apart from movement (that is to say, a form of activity).

In addition, so that teachers have a global view of the forms of energy, we think it is important to eliminate the boundary raised in secondary and university education between energy in mechanics and energy in thermodynamics, which is at odds with the historical origin of the concept. As too few textbooks (e.g. Pérez 2001, pp. 90–92) or science education writers (e.g. Cotignola et al. 2002, p. 283) point out, the total energy of a material system is the sum of its mechanical energy (itself equal to the sum of the kinetic energy and the potential energy of the system considered at the macroscopic level and in relation to other systems) and its internal energy (equal to the sum of the molecular kinetic energy, or thermal energy, and the potential energy of interactions, such as chemical or nuclear energy, of the system considered at the level of its microscopic constituents and independently of other systems). In mechanics, if only mechanical energy is considered, this leaves out, on one hand, the processes of thermal transfer between the studied system and its environment and, on the other hand, the changes in the internal makeup of the system. In thermodynamics, if only internal energy is considered, this leaves out, on one hand, the movement of the system considered at the macroscopic level and, on the other hand, the external fields to which the system is subjected. As for electromagnetic radiation, the form of energy associated with this is unique – electromagnetic energy (which is the sum of the energy of the constituent photons in radiation).

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[27] As observed by Roche (2003, p. 187), 'Rankine attributes this definition to Thomson', who 'in 1849, in an almost casual way […] first used the term energy in print more generally to mean the amount of work any system can perform.'

The definition of energy in terms of capacity to produce change helps to give meaning to characteristic (4) and, in correlation, to the following characteristic:

(5) Energy can be transformed or, in other words, can change form.

Certain writers' main concern is to avoid establishing or reinforcing the substantialist conception of energy in learners' minds. To this end, Coelho (2009, p. 978) suggests describing conservation in conversion processes solely in terms of equivalence. In his view, in Mayer's and Joule's experiments on the conversion of work into heat, conservation can be understood simply through the idea that a quantity (of work) is converted into an *equivalent* quantity (of heat). The idea of the 'indestructibility' and the 'transformability' of the same entity (energy), thus acquiring the characteristic of a substance, is simply not needed. The problem with this minimal approach appears when we pose the question: in what way are the quantities of work and heat equivalent? In our point of view, the only possible response is that they are equivalent in regard to the capacity to produce change.

These experiments on the conversion of work into heat can be described as transformation experiments, or of changing one form of energy into a new form of energy. However, in the absence of a clear distinction between *form of energy* and *mode of energy transfer*, confusion could arise in learners' minds. This type of confusion is often found in certain textbooks in relation to the concept of heat (see Cotignola et al. 2002, pp. 284–286, Papadouris and Constantinou 2011, p. 970). Work and heat are modes of energy transfer. Although in Joule's experiment there was indeed conversion from one form of energy into another, it was the transformation of kinetic energy into thermal energy, occurring simultaneously to a transfer of energy (namely, from the 'paddle' system to the 'liquid' system). The possibility of energy to be transferred or exchanged should thus be considered as a characteristic independent of its possibility to be transformed:

(6) Energy can be transferred from one system to another.

Given that the ideas of heat as a property of a body (a form of energy of a body) or as an independent substance (a sort of fluid) are very frequently held by students and can also persist in some teachers (see Gilbert and Watts 1983, pp. 78–79, Driver et al. 1994, pp. 138–139), it seems essential to explicitly discuss them in teacher training. Three themes seem worth developing. The first simply involves pointing out that the term 'heat' can be replaced by 'thermal transfer'. The second consists of emphasising the meaning of each term in the usual mathematical formula of the first law of thermodynamics: $\Delta U = Q + W$. The term on the left describes the change in internal energy U, which includes the internal forms of energy *of the system*, while the two terms on the right describe the modes of energy exchange (Q is thermal transfer and W is work performed on the system by its surroundings) *between the system and its environment* that are responsible for a change in the internal energy of the system (see Arons 1989, p. 507, van Huis and van den Berg 1993 and Cotignola et al. 2002, p. 287). A third theme consists of exploring the history of the theories of heat (see Brush 1976) stressing four stages: (i) the first part of the nineteenth century, a period of confrontation between the substantialist conception in terms of a fluid (a conserved substance distinct from living force) and the mechanistic conception in terms of the movement of the constituent particles of a body; (ii) the rise and fall of the wave theory in the 1830s (one relic of which is the mistaken idea that heat can be propagated by electromagnetic radiation in the same way as conduction or convection); (iii) the interpretation of the experiments of the conversion of work into heat in the 1840s, contributing to the abandonment of the substantialist conception in favour of the mechanistic conception but with the idea that heat is a form of energy rather than a mode of energy transfer (there was still no clear distinction between 'thermal energy' and 'thermal transfer', the latter term being a synonym of 'heat'); and (iv) the microscopic interpretation of heat in terms of microscopic work at the molecular level in the context of the kinetic theory of gases, allowing heat to be eventually understood as a mode of energy transfer. This historical approach allows teachers to consider the two recurrent mistaken conceptions mentioned above and to clarify why they have been ruled out, rather than simply asserting that they are incorrect.

As energy can be transferred from one system to another, it is possible that the energy of a system can be transferred to and, by the same token, split between large numbers of subsystems in its environment. In this case, one refers to 'dissipation':

(7) Energy can be dissipated in the environment.

Several writers (Solomon 1985, p. 170, Duit 1984, p. 65, Goldring and Osborne 1994, p. 30) have suggested that students' difficulty in understanding the idea of the conservation of energy can be surmounted (at least in part) by first introducing the concept of the dissipation of energy.

To deal with this concept of dissipation in teacher training, we suggest starting from the problem of loss that Thomson confronted and tried to resolve in his articles from 1851 to 1852 (Thomson 1851, 1852, see Guedj 2010): in steam engines, it is observed that only part of the heat is converted into useful work[28]; the other part is lost or 'wasted'. What happens to the part that is lost? Is it a question of 'absolute waste', that is, the destruction of part of the heat? Thomson's response came in two stages. In his 1851 article, he developed Joule's idea according to which energy can never be *destroyed* ('mechanical energy' in his words), but only *transformed*. Therefore, the apparent loss of energy is a loss for human beings (who want to use it in machines) and not an absolute loss: the energy in question is 'lost to man irrecoverably; but not lost in the material world'. In his 1852 article, Thomson further clarifies his response by introducing the fundamental concept of *dissipation*. In a steam engine, part of the mechanical energy dissipates via heat because of friction between different parts of the engine, which are inevitable in practice. As it is 'dissipated', that is, divided between large numbers of subsystems of its environment, this energy is 'irrecoverably wasted'. This historical approach has at least two points to recommend it. First, in experiments that they carry out and/or study, teachers are constantly confronted by this problem of the apparent

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[28] In the viewpoint of current physics, it is a question of the transformation of 'thermal energy' into 'mechanical energy'.

disappearance of energy. Second, Thomson's reasoning allows the clear distinction between the utilitarian aspect (loss of energy for the operation of a machine) and the physics aspect (dissipation of energy in the environment).

All of the elements are now in place to introduce the final characteristic:

(8) The energy of an isolated[29] *system is conserved.*

This characteristic can only be fully understood in light of the other characteristics detailed previously, in particular those relating to transformation and transfer. As Duit writes (1984, p. 59): 'When energy is transferred from one system to another, or when energy is converted from one form to another, the amount of energy does not change.'

Let's reiterate these different characteristics and our definition. The conservation of the energy of a system can only be understood if the conversion between different quantities (what is today called 'kinetic energy', 'thermal energy', etc.) is interpreted as the transformation of the same quantity into different possible forms, that is, different possible expressions. If these different expressions can be seen as expressions of the same quantity, we argue that this is because they represent the same capacity to produce change. Additionally, the conservation of the energy of a system can only be understood as an idealised case where the system does not interact with its environment. When it interacts with its environment, the system exchanges energy. In particular, in the presence of friction, part of the energy of the system dissipates in the environment. In order to avoid the obvious contradiction with the principle of conservation of energy, the total energy of the system and the environment with which it interacts should be considered: if this system and its environment are considered as isolated (which is also an idealisation), then their total energy is conserved, although this is not the case of the energy of the system being studied.

8.4.3 What Purpose Does the Concept of Energy Serve?

Why grant so much importance to the concept of energy in teaching? Why do students need to learn to use it? Ultimately, what purpose does this concept serve? To enable teachers to respond to these questions, teacher training should identify and explain the functions that the concept fulfils in science practice. The description of the emergence of the scientific concept of energy (see Sect. 8.4.1) and what energy is (see Sect. 8.4.2) offers a glimpse of these functions. Here we try to make them explicit:

(F1) *Energy is an unvarying focal point for thinking about variations observed in phenomena.* This point was put forward by Mach as early as the end of the nineteenth century. Speaking about the principle of energy conservation, he wrote: 'An isolated variation that is linked to nothing, without a fixed point of comparison, is inconceivable and unimaginable' (1987 [1883], p. 473). Or as

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[29] An 'isolated system' is defined here as a system that does not interact with its environment.

Papadouris and Constantinou emphasise more recently (2011, p. 966): 'Energy [is] a theoretical framework that has been invented in science so as to facilitate the analysis of changes occurring in physical systems regardless of the domain they are drawn from.' More precisely, describing phenomena in terms of *transformation*, *transfer* and *conservation* of energy allows us to think about observed variations.

(F2) *Energy is a unifying focal point for referring to a large variety of phenomena and making links between them.* This point distinctly emerges from the history of the development of the principle of conservation of energy (see Sect. 8.4.1). To quote Cassirer (1929 [1972], p. 520), energy can be described as 'a point of unity to grasp by pure thought'.

(F3) *The principle of conservation of energy allows predictions to be made.* This predictive function occurs at two possible levels. (i) The principle allows quantitative predictions to be made *in the context of a theory*. For example, in mechanics, the principle of conservation of mechanical energy allows the prediction of the speed of a body at time t_2 given the position and speed of the body at a previous time of t_1. (ii) The principle also allows predictions to be made *in the development of theories*, which can be described as a 'heuristic function'. A famous example of this is that of the role of the principle in the anticipation of the existence of the neutrino. We could also mention the no less important examples of the development of special relativity and quantum mechanics, in which the principle played an explicit role (see, e.g. Einstein 1905; Heisenberg 1972 [1969], pp. 91–92). This heuristic function was emphasised as early as the nineteenth century, for example by Maxwell (1871) who attributes the principle as it was formulated by Helmholtz with an 'irresistible driving power' (see Truesdell 1980, p. 163). More recently, Feynman (1965, p. 76) justifies the recourse to the principle in new fields in this way: 'If you will never say that a law is true in a region where you have not already looked you do not know anything.'

8.5 Conclusion

As we have established in the case of France, energy is an omnipresent concept in school programmes from primary to the end of secondary education and has two main aims: educating students from a scientific point of view and preparing them as future citizens to enable them to take part in social issues that involve the concept of energy. Yet science education literature has shown that the concept of energy is particularly difficult to define and to teach. This is due to the concept itself, principally to the fact that it is highly abstract and polymorphous and thus difficult to define. The difficulties in defining the concept lead to a multiplicity of conceptions (anthropocentric, substantialist, etc.) and confusions (force/energy, forms of energy/modes of energy transfer, etc.) that are equally obstacles to learning. Several teaching strategies have been proposed in science education literature over the last thirty years as alternatives to traditional teaching methods deemed too formal and dogmatic. However, none has distinguished itself as the most convincing method and been retained over the course of time in school programmes.

The new strategy that we advocate differs from previous proposals in two major ways. Firstly, we propose turning the attention to teacher training, which seems an essential precondition to teaching energy, given the complexity of the concept. The aim is thus to develop a teacher training programme that allows educators to better grasp the meaning of the concept, the role it plays in science and to be clear about all the characteristics of energy as well as the recurrent mistaken ideas about it. Secondly, our strategy grants a central role to EHST. We think EHST provides effective ways to throw light on the different aspects of the concept and should be a feature of teacher training. In this article, we have recommended a framework for teacher training based on EHST structured around three main questions: 'What is the origin of the concept of energy?', 'What is energy?' and 'What purpose does the concept of energy serve?'

We have highlighted several points that seem essential to include in teacher training. In particular, it is important that teachers understand that the concept of energy, as currently accepted, has not always been available for scientists and only became stable with the emergence of the principle of conservation of energy, itself resulting from a mutual adjustment between theory and experimentation. We have also tried to show that the definition of the energy of a system as its capacity to produce change is required in order to be able to understand that energy can take different forms and can be transformed. These characteristics, along with the transfer and dissipation of energy, allow the fundamental characteristic of the conservation of energy to be understood. Finally, it seems very important that teachers are aware of three operational roles that the concept of energy plays in scientific activity: its role as an unvarying focal point for thinking about variation, its unifying role and its predictive role.

The teacher training framework on energy presented here needs to be further enriched (with examples of course outlines and teaching sessions on energy) and detailed (to allow for constraints on the ground) and to be subjected to experimentation. Our hypothesis is that this teacher training should lead teachers to profoundly rethink the way in which they approach teaching about energy: in terms of their interpretation of programmes, of their own ideas and those of their students and of their teaching practice. If teachers are clear about the concept of energy and adopt, in light of EHST, a new position regarding how to teach it, it becomes possible to envisage a teaching approach itself based on EHST that can thus truly distance itself from a formal, dogmatic approach. Our wager is that this type of teaching will enable the difficulties in mastering the concept of energy to be overcome more easily. This teaching has yet to be developed.

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Chapter 9
Teaching About Thermal Phenomena and Thermodynamics: The Contribution of the History and Philosophy of Science

Ugo Besson

9.1 Introduction

The role of history and philosophy in science teaching has been studied and debated at great length. It is considered that introducing themes of history and philosophy can give cultural value to science learning, engendering a more critical attitude and a conception of science as an evolving human activity. Moreover, the history of science can help to give sense to science learning. In fact, science teaching constrains to isolate and restructure science subjects in order to adapt them to the students' needs and to the school context. This process can lead to a presentation of scientific topics in a way that hides the cultural and social references of the problems in answer to which scientific theories had been formed and avoids the methodological and philosophical aspects which can give general cultural sense to scientific issues and provide a deeper understanding. This can produce a fragmentary, more algorithmic than conceptual knowledge. Studying *case histories* involving significant historical or philosophical aspects can contribute to reconstructing the atmosphere of debate and controversy and provide the technical and economic background that constituted the context of science development (Stinner et al. 2003). The US National Science Education Standards (1996, Chap. 6, p. 107) 'recommend the use of history of science in school programs to clarify different aspects of scientific inquiry, the human aspects of science and the role that science has played in the development of various cultures'.

Research on common sense conceptions has renewed the debate on the role of history in science teaching because many of these conceptions are found to be similar to ancient ideas or theories. Resembling the theory according to which ontogeny recapitulates phylogeny, it is supposed that individual cognitive development can

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recapitulate in some way the historical development of science. It has been supposed that, confronted with such ideas and theories, students would recognise some features of their own conceptions, discussing and reviewing them, with conceptual change sequences similar to the historical ones (Campanaro 2002). However, such proposals have been criticised for their often too simplistic analogy between ancient theories and common thought and because of the strong differences in the context, the meaning of concepts and ideas used and the mental and logical processes involved (Carey 1988; Nersessian 1995). Nonetheless, these analogies have some validity, even if in a limited form. For example, Piaget and Garcia (1983) emphasised them strongly.

History and philosophy of science can contribute to improving students' understanding of the conceptual, procedural and contextual aspects of science (Teixeira et al. 2012; Wang and Marsh 2002). They can also positively contribute to a better understanding of scientific methods, the nature of science and the relationships between science, technology and society and to metacognitive learning (Matthews 1994). The conceptual analysis of physics theories and history can help to answer the questions of how we know what we know and how we discovered it.

Examples from the history of science can provide a repository of strategic knowledge of how to construct, modify and communicate scientific representations, and science educators could choose, integrate and transform these resources into instructional procedures (Holton 2003a; Nersessian 1995; Seroglou and Koumaras 2001).

Moreover, many problems, models and explanatory frameworks used in the early historical development of a scientific topic are more in resonance with the preferences of students and of common reasoning, which is often centred on dynamical, causal, qualitative and analogical reasoning (Besson 2010). There is sympathy between the beginner and the pioneer.

In this way, the topic of thermal phenomena and thermodynamics is fertile because it relates to various epistemological and philosophical themes. Its history is strongly linked to the themes of relationships between science, technology and socio-economic problems; residues of ancient abandoned theories are still present in current scientific language and in textbooks; and many students' conceptions are similar to ideas and reasoning of ancient theories.

The historical conceptual development of thermodynamics is especially interesting for teaching because it can show the reasons for paradigm shifts in research communities (e.g. on the nature of heat and the notion of temperature), based on a progression moving from phenomenological observations to qualitative and then mathematical models and laws, in an increasing process of abstraction. This historical progression can assist learning progression and challenge students' alternative ideas.

This chapter will present the main results of research on students' conceptions and difficulties about thermal phenomena (Sect. 9.2), a review of research involving the use of history and philosophy in teaching thermal phenomena and thermodynamics (Sect. 9.3), some examples of philosophical themes and of case histories of didactic interest together with their teaching and learning implications (Sects. 9.4 and 9.5) and some suggestions for further research and development (Sect. 9.6).

9.2 Students' Conceptions and Conceptual Difficulties About Thermal Phenomena

Much research has been conducted on students' conceptions and difficulties about thermal phenomena.[1] Students show difficulties in distinguishing between extensive and intensive quantities, in particular between heat and temperature. They often use a mixed temperature-heat notion or consider the temperature of an object as a measure of *the level of heat*. Sometimes heat and cold are both considered as substances that can be transferred from one body to another. Students mainly reason in terms of object properties instead of processes and may attribute to the materials the quality of being or keeping warm or cold (an ice cube melts more quickly if it is wrapped in a wool cloth because wool 'is warm or keeps warm'). They may also consider the existence of a maximum possible temperature for a given material. Work is generally not connected to temperature changes. The prevalent idea is that only heat exchanges can cause an increase or decrease in the temperature of an object. This idea also survives among university students and can also be found among science teachers.

Concerning microscopic models of gas, students often attribute to molecules the same properties of macroscopic objects and tend to consider only one variable at a time in a linear causal reasoning (Rozier and Viennot 1991).

Chiou and Anderson (2010) characterise four patterns of students' interpretative frameworks of heat: first, heat is treated as an intrinsic property of a substance (wood is hot, ice is cold); second, hotness and coldness are treated as material substances which can move from one object to another; third, heat is treated as a nonmaterial entity, caloric flow, which propagates from objects at higher temperatures to objects at lower temperatures; and fourth, a scientifically acceptable view, in which heat refers to a transfer of energy due to a temperature difference. According to the authors, 'The sequence of these four frameworks also represents the developmental stages of peoples' conceptions of heat, developing from a naive view toward a more scientific one'.

Heat is often considered a quantity which is conserved in a cyclic thermodynamic process, as a property of the system or a state function, and it is used as synonymous with internal energy or with thermal energy, i.e. of the part of internal energy involved in the temperature changes.

Some students' difficulties with the concept of heat derive from the difference between its meaning in common language and in the language of science. Some ambiguities also appear in textbooks (see Doige and Day 2012; Leite 1999) and differences are found in the definitions of heat across textbooks of different disciplines (physics, chemistry, biology and earth science). Many physics and chemistry

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[1] See Arnold and Millar (1996), Besson et al. (2010), Chiou and Anderson (2010), Clough and Driver (1985), Cochran and Heron (2006), Cotignola et al. (2002), de Berg (2008), Erickson (1979, 1980), Erickson and Tiberghien (1985), Jasien and Oberem (2002), Leinonen et al. (2009), Lewis and Linn (1994), Sciarretta et al. (1990); Shayer and Wylam (1981), Stavy and Berkovitz (1980), Wiser and Amin (2001), and Wiser and Carey (1983).

textbooks in the 1960s and 1970s defined heat as the kinetic energy associated with molecular motion and thus as a property of a system or as a form of energy degraded or disordered. By contrast, science education literature has stressed that heat has to be considered as a process quantity, a transfer of energy due to a difference in temperature. More recently, physics textbooks have assumed this view by referring to heat as energy in transit or as a mechanism or process of energy transfer, whilst many life science and earth science textbooks still present a definition of heat as energy contained in a system.

Difficulties in differentiating the meaning of heat, work and internal energy hinder the understanding of the laws of thermodynamics. In fact, older students also show difficulty in applying the first law of thermodynamics, often considering heat as a state function (Loverude et al. 2002; Meltzer 2004), and misunderstand the second law (Kesidou and Duit 1993). The language generally used in textbooks can reinforce some common erroneous ideas, referring to ‘work done’ but to ‘heat given’, ‘received’ or ‘lost’. These last expressions convey the idea that a body *possesses heat* in order to give it and are clearly fossil residues of the old conception of heat as fluid (Besson and De Ambrosis 2013). Moreover, any distinction between heat and work disappears at a microscopic level because the interactions are of the same type. The difference is in their coherence or incoherence and appears only at macroscopic or mesoscopic levels where a large number of molecules are involved (Besson 2003).

Students usually lack considering or consider incorrectly the infrared thermal radiation in thermal processes of energy exchange (Besson et al. 2010). There is often confusion about whether thermal radiation must be considered as a way of heat transmission, as work or as a third specific modality of energy exchange. There is no universal agreement in the research literature on this point. Most textbooks choose the first option, by considering thermal radiation as the third way of heat transmission, after conduction and convection, but this can implicitly suggest that radiation and heat have the same characteristics, thus contributing to students' difficulties. The historical development of the idea of thermal radiation and the study of its characteristics compared to the properties of light shows how the process of differentiation was a long one and required both experimental and theoretical efforts (Besson 2012). In physics history the term *radiant heat* has been used for a long time, even if Maxwell wrote in 1871:

> The phrases radiation of heat and radiant heat are not quite scientifically correct, and must be used with caution. Heat is certainly communicated from one body to another by a process which we call radiation. We have no right, however, to speak of this process of radiation as heat … when we speak of radiant heat we do not mean to imply the existence of a new kind of heat but to consider radiation in its thermal aspect. (Maxwell 1871, pp. 15–16)

And later he stressed the difference in behaviour and in nature between heat and radiation by means of arguments that can be usefully proposed to students:

> What was formerly called Radiant Heat is a phenomenon physically identical with light. When the radiation arrives at a certain portion of the medium, it enters it and passes through it, emerging at the other side … as soon as the radiation has passed through it, the medium returns to its former state, the motion being entirely transferred to a new portion of the

> medium… Now, the motion we call heat can never of itself pass from one body to another unless the first body is, during the whole process, hotter than the second. The motion of radiation, therefore, which passes entirely out of one portion of the medium and enters another, cannot be properly called heat. (Maxwell 1875, pp. 376–377)

Some of the common conceptions described above recall historical ideas and models now abandoned. Students speak about 'heat contained in a body' as a substance that can pass from one body to another, in a way that resembles the ancient theory of *caloric fluid*. Cotignola and others (2002) analysed students' misunderstanding of basic thermodynamic concepts on historical grounds and concluded that

> The persistence of some ideas from the caloric model are found to be reinforced by magnitude names and unit definitions that were brought up at the early stages of thermodynamic development … Many thermodynamic terms, such as latent heat or heat capacity, were formulated as part of the caloric theory. … The resulting mess becomes one of the main obstacles in the understanding of thermodynamic concepts. (Cotignola et al. 2002, p. 286)

9.3 Research on the Use of History and Philosophy in Teaching Thermal Phenomena and Thermodynamics

History and philosophy of science can be implemented in teaching thermal phenomena and thermodynamics in various ways:

1. Discussing some epistemological, methodological, philosophical specific or general problems connected with the topic in order to improve students' learning, to supply deeper and meaningful knowledge and understanding of the topic, not only technical and algorithmic, and to introduce themes and problems concerning the nature of science.
2. Realising a teaching path that follows essentially the historical path with the connected epistemological, cultural, social and technological themes.
3. Developing some case histories of relevant didactic, cultural, scientific and methodological meaning.
4. Using some historical models, examples, analogies or experiments in order to help students to surmount specific erroneous conceptions and conceptual difficulties.
5. Developing a historical and epistemological analysis of the topic on which to elaborate a didactic reconstruction and design a teaching path (in this case it is not proposed to introduce themes of history and philosophy of science in science courses but to utilise them to find a more effective way for improving students' learning).

Some examples are given below of research and books involving the use of history and philosophy in teaching thermal phenomena and thermodynamics.

The famous book, *Harvard Case Histories in Experimental Science* (Conant 1957), presented eight case histories and the third one concerned thermal phenomena: 'The early development of the concepts of temperature and heat: the raise and decline of the caloric theory' (prepared by Duane Roller, pp. 117–214). It included five sections (Evolution of the thermometer, Black's discovery of specific and latent heat, Rumford's investigation of the weight ascribed to heat, Rumford's experiments on the source of heat that is excited by friction and Davy's early work on the production of heat by friction) and ended by proposing 88 final questions suitable for students. The purpose was to 'assist the reader in recapturing the experience of those who once participated in exciting events in scientific history … transporting an uninformed layman to the scene of a revolutionary advance in science' (p. IX). The aim was also to illustrate the methods of modern science, considering that familiarity with those methods will increase the understanding of the work of scientists today (p. X). The case history presented two rival schemes in conflict and showed how the transition to a new theory or conceptual scheme is not easy and that old ideas are tenacious.

The *Project Physics Course* (1970), directed by F. J. Rutherford, G. Holton and F. G. Watson, presented many historical aspects of the birth of thermodynamics, its connections with the development of steam engines and the industrial revolution, the discovery of first law of thermodynamics and the debate on the meaning and consequences of the second law (irreversibility, the thermodynamic arrow of time, the heat death of the universe). The authors wanted to 'present not only good science, but also something solid on the way science is done and grows, on the scientific worldview, on how the sciences are interrelated with one another and with world history itself' (Holton 2003b, p. 780). The Project was the object of a large process of evaluation with thousands of students showing positive results (Welch 1973). A new version of the course was published in 2002 (Cassidy et al. 2002, *Understanding Physics*).

Baracca and Besson (1990) proposed using the historical thread of the theories on the nature of heat, the research of Smeaton, Lazare Carnot and Sadi Carnot, and the development of steam engines in the industrial revolution, to introduce thermal phenomena, the laws of thermodynamics and the problem of engine efficiency, especially developing the hydraulic analogy of heat.

Stinner and Teichmann (2003; see also Begoray and Stinner 2005) created a dramatisation of a fictitious but historically based discussion on the age-of-the-Earth problem set in the Royal Institution of London among William Thomson (Lord Kelvin), T. H. Huxley, Charles Lyell and Hermann von Helmholtz. The play was partly based on a lively exchange that occurred between Huxley and Thomson, starting in 1868. In the second half of the nineteenth century, the question of the age of the Earth and the Sun elicited great excitement, both in scientific circles and among the general public. There was no doubt that the sources of the sun's energy, and therefore the existence of the Earth, were limited. Guided by an interpretation of biblical chronology, Bishop Ussher calculated the age of the Earth as 1,650 years. Based on the laws of thermodynamics and the principle of energy dissipation, Kelvin concluded that the Earth could be aged between 20 and 400 million years but not be older. The problem was especially interesting and challenging for physicists but also interested the larger public because it involved philosophical and theological questions and two newly discussed theories, Darwin's Evolution in biology and uniformitarian theory in geology, which assumed an age of Earth of many hundreds of millions of years (see Sect. 9.4.1), and both theories were opposed by Kelvin. The drama was presented to university students and in front of a large audience, and parts of the play were successfully used by teachers in their high school classrooms. The authors argue that historical dramas such as this one can be used for all students to promote learning of particular aspects of science, including the social context of science, science as a human activity and the centrality of debate in scientific change (see also Stinner 1995). Using drama is one of several 'units of historical presentation' that were used by Stinner and his co-workers in teachers' education; others were vignettes, case studies and confrontations (see below).

Stinner and associates (2003), in a general study about the use of history in science teaching, presented some guidelines for designing historical case studies and for context-based teaching. They also proposed the debate on the nature of heat between Rumford and the sustainers of caloric theory as a 'mini-confrontation', suitable for upper secondary school. 'Many of the experiments that Rumford performed can be replicated by students … before doing so, teachers could present the caloric theory along the lines previously suggested and discuss it as an explanatory theory for many everyday phenomena. Following that, teachers could set up experiments inspired by Rumford' (p. 629).

Metz and Stinner (2006) developed teaching activities centred on the analysis and replication of historical experiments. The activity was organised as a *narrative* divided into four parts: introduction, experimental design, experimental results and analysis and interpretation of data and explanation. They used some of Rumford's experiments on heat which could easily be adapted for the classroom. In these investigations, Rumford was interested in determining what materials afforded the best insulating protection and measured the cooling time of a warm container. The introductory part of the narrative established the context, including some biographical information, and presented a problem and/or confrontation. Students read an excerpt from Rumford's paper of 1804, perform the experiment, compare their results to Rumford's results and discuss the discrepant results and the proposed explanations. As they interact with the history throughout the investigation, students develop scientific processes and address questions on the nature of science.

Chang (2011) discussed the possible roles and aims of historical experiments in science education. He considered three different objectives: to advance the understanding of the history of science, to refine our philosophy of science and the conceptions of the nature of science (NOS) and 'to improve scientific knowledge itself – that is, to gain more, better, or different knowledge of nature than current science delivers'. Focusing on this third aspect, he illustrated two case histories, the first one concerning the anomalous variations in the boiling point of water. Indeed, around 1800, many scientists (he considered especially Joseph-Louis Gay-Lussac, Jean-Baptiste Biot and Jean-André De Luc) observed that 'the boiling temperature of pure (distilled) water under standard pressure depended greatly on the material of the vessel employed, on the exact manner of heating, and on the amount of dissolved air present in the water'. He pointed out that at various levels of science education, we teach that pure water under standard pressure always boils at 100 °C, but the case history has shown that ‘we do it in a patently incorrect way’. He considered the function of history and philosophy of science (HPS) as ‘complementary science’, ‘which complements specialist science, neither hostile nor subservient to it … HPS in this complementary mode is not about science; rather, it is science, only not as we know it’. In this line of work, the proposed historical experiments play the role of ‘complementary experiments’, in which what matters is *physical replication*, not *historical replication*, and they can improve our knowledge of nature and aid science education.

Wiebe and Stinner (2010) suggested the use of interactive historical vignettes, presented in the form of guided readings, in which the concepts are embedded into the historical contexts, to help the students’ understanding of gas behaviour. They presented the problems of pressure-temperature and volume-temperature relationships and subsequently the historical context of the explanations of gas behaviour using the particulate nature of matter and the kinetic molecular theory.

Viard (2005) used an alternative strategy to teach the concept of entropy, which consisted of getting the students to read and interpret excerpts from Carnot, Clausius and Boltzmann. He considered that the history of thermodynamics can provide resources for a direct and simple teaching path for introducing entropy to students.

Zambrano (2005) developed ‘a curricular sequence based on a historical study of conceptual change in science’. He did not present history directly to students as course content, but he utilised history as a reference for designing a learning path aimed to improve the students’ conceptual change from their previous conceptions to correct scientific knowledge. He wanted to show how the history of science can illuminate the teaching and learning of scientific concepts in school:

> Our belief in this case is that the change necessary to go from caloric theory to thermodynamic theory of heat and temperature concepts can illuminate the changes pupils experience in changing from their initial concepts about heat and temperature to expert’s concepts. … The historical construction process of the concepts of heat and temperature, analyzed in the light of the different obstacles against its progress, allow us to elaborate the corresponding teaching educative sequence based on its historical epistemological order. (Zambrano 2005, pp. 1 and 8)

Mäntylä and Koponen (2007) developed an epistemological reconstruction of temperature as a measurable quantity. They did not want to produce historical reconstructions ‘but instead to use HPS as a starting point for developing and designing suitable didactic solutions, which can be called didactic reconstructions for teaching’ (p. 292). The reconstruction parallels the historical development, but its intention is not to be a historically authentic path. The history is interpreted from the point of view of modern conceptions, ‘because the goal is to teach physics, not the history of physics’. Moreover, they think that this reconstruction also ‘conveys a more correct view of the role of measurements in the production of scientific knowledge’. A conceptual analysis of the historical development is needed, even when ‘the purpose is to produce teaching solutions fostering the development of modern conceptions rather than giving an authentic picture of historical developments’.

De Berg (2008) proposed the use of analogies based on the historical caloric theory in order to help students to clearly distinguish between heat and temperature,

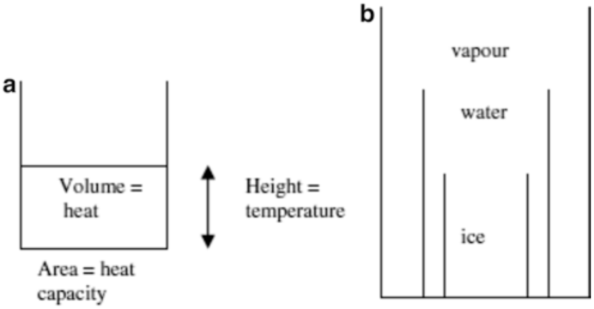

Fig. 9.1 Adaptation of the model of Irvine and Dalton representing (**a**) the difference between heat and temperature, (**b**) the effect of phase transitions (De Berg 2008, p. 15, Fig. 9.2)

explain phase changes from solid to liquid to gas and introduce the idea of absolute zero of temperature. He used and adapted a model originally elaborated and developed by Irvine (1743–1787) and Dalton (1766–1844) (see Fig. 9.1). According to the author, these analogies do help students understand the difference between heat and temperature and the concept of heat transfer, but they can also reinforce the material view of heat against the kinetic view. Nevertheless:

> The material view of heat can be thought of as having been transformed from a theory about the nature of heat to an analogy useful for pedagogical purposes and that may not be necessarily a bad thing provided one is aware of the limitations of analogies … Also, one's attitude to outdated models and theories grows into one of respect rather than one of disdain when presented with relevant historical cases. (De Berg 2008, pp. 90–91)

In the context of the European project HIPST (History and Philosophy in Science Teaching), two case studies concerned thermodynamics:

(a) Temperature – what can we find out when we measure it? (Oversby 2009, UK)

> The topic of temperature is fascinating because it begins with an unclear understanding by historical scientists about its nature, and about how to measure it. This parallels the position of the 11 year old students in the pilot program. The historical search for a suitable measurement is inextricably bound up with creating instruments to do the measuring, and the lack of clarity about what was being measured. … We have used links to Drama in producing play scripts of historical events, and to English in the form of newspapers to present historical information.

(b) Steam, Work, Energy (Brenni et al. 2009, Florence, Italy)

> This case study concerns the formulation and production of a kit for high school physics teachers (students aged 14–19) to supplement their lessons on thermodynamics with elements offering an historical contextualization of how several fundamental laws of physics were discovered, and how certain concepts have become structured in time… evidences the connection between science, technology and society … it shows how practical necessities and empirical-technical solutions gave rise to the premises for forming new theories … how the technological innovation of the steam engine and its successive improvements made possible also by new scientific acquisitions, profoundly transformed society and its organization… it contains videos showing instruments in operation from the historical collection.

9.4 Philosophical Problems of Thermodynamics and Their Implications for Teaching

Thermodynamics poses many important epistemological and philosophical problems which can be accessible and useful for secondary education and which are not separated from the content but entangled with it. As Prigogine wrote:

> It is the singularity of physics such as we know it still today: the metaphysical discussions are not superimposed arbitrarily on strictly scientific questions, but depend on those in a crucial way. (Prigogine and Stengers 1988, p. 37)[2]

Some philosophical themes or problems of didactic interest can be proposed in teaching and are relevant for well-founded learning:

- The meaning, interpretations and implications of the second law (irreversibility, time arrow, statistical and probabilistic laws and determinism)
- The relationships between macroscopic properties and microscopic structures, reductionism, emergence and primary and secondary qualities
- The nature of thermodynamics theory, as a theory of principles not constructive, its structure, its relationships and its differences from classical mechanics
- The relationships between science, technology and societal demands, which have special features in the case of thermodynamics
- The construction of a physical quantity such as temperature

In this section, I will discuss some philosophical issues which can be proposed, in appropriate form, to students of high school and university.

9.4.1 Origin and Meaning of the Laws of Thermodynamics

The first law of thermodynamics concerns essentially the energy conservation law, and therefore in this book it is treated in the chapter on energy. Instead, here some considerations are given on the second law of thermodynamics, which offers many stimuli for creating multidisciplinary didactic activities.

Thermodynamics began as a theory of thermal engines and retained for a long time some characteristics derived from this beginning. This is also true for the second law of thermodynamics, especially in the Kelvin formulations concerning useful work, energy dissipation and degradation of energy (Thomson-Kelvin 1851, 1852). The emancipation from this utilitarian origin, linked to technical, economic and practical aims, happened only with the works of Clausius and Gibbs. Thomson (Kelvin) and Tait were very attached to these early ideas and spoke about dissipation, degradation and not available energy, i.e. energy which is not annihilated but is unusable for mankind, in some formulations distinguishing between the physics of living

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[2] All quotations that were in French or in Italian in the original have been translated into English by the author of the present paper.

beings and of the inanimate world. This tendency is also linked to metaphysical and theological choices and arguments, e.g. that God would have created the world with a total energy which, being a divine creation, is conserved, cannot be consumed and is stable and eternal, whilst what concerns man is perishable and temporary. In some way, in the contrast between the approaches of Kelvin and Clausius, there is an opposition between a man who yearns not to lose useful resources and possibilities and a man who wants to understand nature ignoring human concerns.

Subsequently, the situation changed remarkably and the debate on the meaning and implications of the second law involved wider and more general problems, such as the age of the Earth and of the universe, cosmological themes, the heat death of the universe, evolution and religious implications. Later, statistical entropy was connected with information theory (Shannon 1948) and it was identified as a measure of the lack of information (Jaynes 1957). Moreover, some thermodynamic ideas and words have been assumed in other fields, like economics, ecology and sociology (e.g. social entropy, human thermodynamics, thermoeconomics).

Kelvin used the energy dissipation principle and the heat conduction law to calculate that the present temperature conditions on Earth could have existed for only 20–100 million years and used this result for contrasting the uniformitarian theory in geology, which assumed constant conditions over hundreds of millions of years, and Darwin's theory of evolution, which Kelvin thought 'did not sufficiently take into account a continually guiding and controlling intelligence'. Stinner and Teichmann (2003) designed a teaching activity on this controversy about the age of Earth (see Sect. 9.3).

Currently, different senses of entropy can be found in scientific and popular literature: thermodynamic, statistical, disorder and information senses (Haglund et al. 2010). The disorder metaphor goes back to Helmholtz and Boltzmann and is very common in popularisations and textbooks as an aid to forming an intuitive image of entropy, but it is criticised because it would be conceptually misleading (Lambert 2002 considered it as 'a cracked crutch for supporting entropy discussions') and could lead students to erroneous conclusions in thermodynamics tasks (Viard 2005). Styer (2000) illustrated examples of increased entropy accompanying increased 'order', in clear contradiction with the *entropy as disorder* view. On the other hand, order and disorder are partially subjective terms, and they can be differently interpreted by different observers.

9.4.2 Irreversibility and Time Arrow, Mechanics and Thermodynamics

Some problems can be posed concerning the relationship between thermodynamics and mechanics. The reversible laws of mechanics, with temporal symmetry, seem to oppose the second law of thermodynamics, with the time arrow (the expression was introduced by Eddington in 1928 in his book *The Nature of the Physical World*), which is evident in daily experience. In this sense mechanics is in strong contrast with common experience, a problem that was taken into account only very late, just when thermodynamics included in its foundations the irreversibility of actual physical processes.

The notion of equilibrium is very different in mechanics and in thermodynamics. It is only by the effect of friction and of energy dissipation that an oscillating pendulum will stop in its equilibrium position after a number of oscillations, whilst in the frictionless ideal case it will never stop. During an oscillation the pendulum can reach and immediately abandon the equilibrium position and can pass through it before or after another position, except if it is placed there motionless by an external force.

By contrast, in thermodynamics a system tends spontaneously towards an equilibrium state and once reached it remains there; the equilibrium state is the term of an evolution without return (Stengers 1997, pp. 73–75). One could say that, if the physics of Galileo and Newton eliminated the distinction between the world of the Earth and that of the skies, between the disorder and the corruption of the former and the rational and incorruptible order of the latter, here a similar fracture seems to appear between the irreversible and dissipative world described by thermodynamics and the classical mechanics that governs the motion of ideal pendulums, perfectly elastic bodies, and of celestial bodies (Maxwell called it 'The Queen of the Skies'). Mechanics seems to have to neglect 'the impediments of the matter' (Galileo 1632 *Dialogue,* second day) and apply some opportune idealisations in order to represent actual phenomena correctly. Friction phenomena appear to be the bridge between the two approaches but their explanation in terms of mechanics asks for conjectures on complicated effects of a great number of microscopic or mesoscopic entities (see Besson 2001 and 2013).

The problem is then posed of the coherence between the two theories and the possible prominence of one over the other. Is the second law of thermodynamics only an appearance behind which there are reversible microscopic phenomena or is it a fundamental law of nature? Is it only a statistical result indicating an improbability or is it an exact law that allows the re-establishment of a *new alliance* between science and human experience (as supported by Prigogine)? Must one try *to explain* thermodynamics by means of mechanics or is it necessary to modify mechanics? Is unidirectional time a phenomenological, not fundamental, property, a sort of secondary or emergent quality such as colour and flavour, due to the fact that we are beings of an intermediate dimension? Is it a property or quality that would not exist for a microscopic being like Maxwell's demon, which can handle single molecules (see Sect. 9.4.3), or for the super-intelligence imagined by Laplace, which can know and calculate all the positions and velocities of particles? We could imagine a dialogue between mechanics and thermodynamics which is similar to the one between reason and senses written by Democritus (fragment B125), by replacing colour and flavour with irreversibility and the time arrow:

> The intellect says: By appearance there is sweetness or bitterness, by appearance there is colour, in reality there are only atoms and the void. The senses answer: Ah foolish intellect! You get your evidence from us, and yet do you try to overthrow us? That overthrow will be your downfall.

Later in his life, Boltzmann concluded that the time arrow is an appearance which does not belong to the entire universe, and inversely the direction of time is determined by the direction of entropy increase:

> For the universe as a whole the two directions of time are indistinguishable, just as in space there is no up or down. However, just as at a certain place on the Earth's surface we can call 'down' the direction toward the centre of the Earth, so a living being that finds itself in such a world at a certain period of time can define the time direction as going from less probable to more probable states (the former will be the 'past' and the latter the 'future') and by virtue of this definition he will find that this small region, isolated from the rest of the universe, is 'initially' always in an improbable state. (Boltzmann 1897, English translation in Brush 2003, p. 416)

9.4.3 Statistical Mechanics and Thermodynamics, Probability and Determinism

The process obtained by means of a time reversal of a natural process, such as inverting the order of the frames of a film, does not exist in nature. Can we explain this fact by a model in which the matter is constituted of a large number of microscopic particles? Can we understand the irreversible phenomena and the consequent increase of entropy in terms of movement and interaction of a large number of atoms? This is the problem of the explanation of the irreversible macroscopic laws in terms of the reversible microscopic laws regulating the movement of atoms. When the macroscopic thermodynamic properties of heat and temperature or the gas laws are explained in terms of behaviour and movement of small particles, some philosophical problems arise naturally, such as reductionism, emergent properties and supervenience (Callender 1999).

The bridge between macroscopic and microscopic levels passes through molecular atomic theory and the kinetic theory of gases and then the statistics of Maxwell and Boltzmann. In general, these issues lead to the problems of the role of probability in physics and in the explanations of natural phenomena and the relationship between the knowing subject and the physical reality, issues that were to be resumed with new depth by quantum mechanics. Probability would have the task of articulating our uncertain world with a supposed objective reality, which is governed by deterministic and exact laws.

Boltzmann seemed to solve the problem for a gas with his H-theorem, showing that collisions between molecules lead towards the equilibrium distribution and that a special function H (in the original article this function was called E) always decreases with time until reaching a minimum value. For a gas in thermal equilibrium, the H-function is proportional to minus the entropy as defined by Clausius for equilibrium states, and Boltzmann considered it as a generalised entropy valid for any state, so he considered that he had demonstrated by means of a mechanical model that entropy always increases or remains constant. Some objections arose soon after, such as the *reversibility paradox* of Loschmidt, the *recurrence paradox*

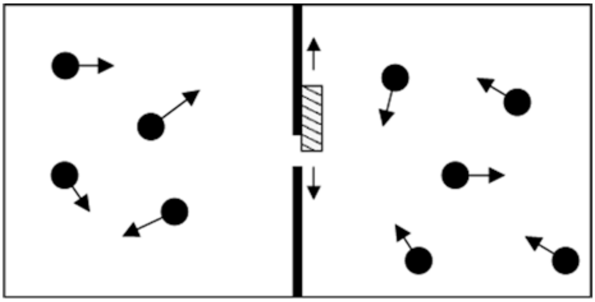

Fig. 9.2 An illustration of the Maxwell's intelligent demon. The two boxes communicate through a little door. The demon opens and closes the door so as to allow the faster molecules to move from the right box to the left and the slower molecules in the opposite way. As a consequence, the temperature of the gas in the left box becomes higher than the temperature of the gas in the right box, so contradicting the second law of thermodynamics and making the entropy of the whole system diminish

of Poincaré-Zermelo and the *reversibility objection* that it would be impossible to deduce the irreversibility from laws and collisions which are reversible, the only way being to enter irreversibility at the molecular level. Boltzmann answered these objections, by adding further hypotheses to his model and assuming that in fact it is possible that entropy decreases, but it is extremely improbable, so transforming in improbability the impossibilities enounced by the second law of thermodynamics. This was also the idea of Maxwell:

> This is the second law of thermodynamics, and it is undoubtedly true as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being … would be able to do what at present is impossible to us… He will thus, without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics. This is only one of the instances in which conclusions which we have drawn from our experience of bodies consisting of an immense number of molecules may be found not to be applicable to the more delicate observations and experiments which may suppose made by one who can perceive and handle the individual molecules which we deal with only in large masses. In dealing with masses of matter, while we do not perceive the individual molecules, we are compelled to adopt what I have described as the statistical method of calculation, and to abandon the strict dynamical method, in which we follow every motion by the calculus. (Maxwell 1871, pp. 358–359)

Thomson-Kelvin (1874) used the term *intelligent demon* to refer to a being that could theoretically reverse the dissipation of energy and the entropy increase (Fig. 9.2). Maxwell's demon spawned much discussion for many years, and different solutions were proposed to solve the paradox (see, e.g. Collier 1990; Daub 1970). It was considered that all measurements need an energy cost, in which dissipation would compensate the entropy decrease due to the relocation of molecules. However, later some authors showed that measurements could be performed with a zero or very low energy expenditure. On the other hand, to erase and rewrite the demon's memory, where the information must be stored, energy dissipation is required in an amount which at least compensates the entropy decrease due to the demon's action (see Landauer 1961, who considered that erasing a single bit of information implies energy dissipated into the environment $\geq kT \cdot \ln 2$).

It is strange that all these objections were general considerations or counterexamples, which did not dispute the details of the Boltzmann demonstration. Boltzmann used a gas model consisting of a set of many gas molecules:

> Each molecule is a simple point mass, … two molecules interact only when they come very close together … perhaps the two molecules rebound from each other like elastic spheres… As for the wall of the container that encloses the gas, I will assume that it reflects the molecules like elastic spheres. (Boltzmann 1872, English translation in Brush 2003, pp. 266–267)

He specified that this model showed 'a precise mechanical analogy with an actual gas'. Nevertheless, the movement of a gas of elastic spheres is reversible, and it does not tend to equilibrium. The mathematical model developed by Boltzmann implied irreversibility and tendency towards equilibrium; therefore, it represents well the behaviour of real gases, but it does not represent a gas of elastic spheres correctly.

What do the objections to Boltzmann show? That the second law is not valid, that thermodynamics is irreducible to mechanics or that mechanics must be modified? Or that the employed mechanical model does not represent the physical situation correctly? These questions can open an interesting thread about the role of models in science, their relationship with physical reality and the effects of supplementary simplifications and hypotheses that scientists introduce in order to develop mathematical calculations and obtain specific verifiable results (in this case, e.g. the hypotheses on particular initial conditions or the use of continuous functions to describe finite numerable sets of molecules).

New arguments arose from quantum mechanics and the idea of the impossibility of simultaneous exact determination and definition of the position and velocity of molecules and also from the consideration that a little imprecision or variation in the reversing of all velocities can dramatically change the evolution of the system, quickly redirecting it towards states of increasing entropy. A similar idea was already noticed by Kelvin in 1874:

> If we allowed this equalization to proceed for a certain time, and then reversed the motions of all the molecules, we would observe a disequalization. However, if the number of molecules is very large, as it is in a gas, any slight deviation from absolute precision in the reversal will greatly shorten the time during which disequalization occurs. (Thomson-Kelvin 1874, p. 331)

In addition, it was noticed that the unavoidable small outside influences, which are unimportant for the evolution towards states of entropy increasing, greatly destabilise evolution in the opposite direction when it is aimed at a very small region of the phase space (see Lebowitz 1999).

9.4.4 Nature of Science, Explanations and Models in Thermodynamics

Thermodynamics shows various characteristics which are different from mechanics and electromagnetism. It is not a *constructive science* but a *science of principles*. It does not study or explain how the processes happen and how phenomena are produced, but rather it establishes constraints and tendencies, defines a background and utilises different typologies of explanation and causality (see Wicken 1981). The language of thermodynamics introduces specific new terminologies, different from mechanics and electromagnetism; it speaks about system, state, transformation, reversibility, state equation, adiabatic, entropy, internal energy, etc., terms that create difficulty of interpretation among students, also because they are not always clearly defined and explained in textbooks.

Thermodynamics developed initially as a dynamical theory of heat (as it was the title of one of Kelvin's first works on thermodynamics, see Thomson-Kelvin 1851), with the programme of explaining thermal phenomena by means of the dynamic behaviour of microscopic particles forming the matter. However, the difficulties in carrying out this programme in a complete and satisfactory manner led many scientists to the idea of developing this science in an autonomous way, independently of particular theories and models on the microscopic constitution of bodies. Facing the difficulties of explanations based on atomic models, the same idea of the actual existence of atoms was put in doubt by many scientists at the end of the nineteenth century and also by Planck:

> The second law of thermodynamics, logically developed, is incompatible with the assumption of finite atoms. … Yet there seem to be at present many kinds of indications that in spite of the great successes of atomic theory up to now, it will finally have to be given up and one will have to decide in favour of the assumption of a continuous matter. (Planck 1882, quoted in Brush 1976, pp. 641–642)

It is interesting to notice that this happened in spite of the fact that the kinetic theory of gases had already led to important results, with Clausius explaining pressure and temperature, and especially with the more sophisticated study of Maxwell, who also succeeded in foreseeing an unexpected experimental result like the independence of the viscosity of a gas from the density, over a wide range of densities.

Thermodynamics has become, for many scholars, the model of a theory independent of structural details of constituents of matter which are not directly observable. It has also become the prototype of a scientific theory for philosophers supporting positivist, conventionalist or instrumentalist conceptions of science, like Mach, Duhem, Ostwald and the supporters of energetics. The debate goes back to the works of Fourier and Poisson in the first decades of the nineteenth century. Fourier (1822) sustained the autonomy of his theory of heat and heat conduction, expressed by mathematical equations, from mechanics and from models on matter structure, and criticised the reductionism to mechanics:

> Whatever may be the range of mechanical theories, they do not apply to the effects of heat. These make up a special order of phenomena, which cannot be explained by the principles of motion and equilibrium … The principles of the theory are derived, as are those of rational mechanics, from a very small number of primary facts, the causes of which are not considered

> by geometers, but which they admit as the results of common observations confirmed by all experiments. (Fourier 1822, pp. II–III and XI)

Fourier's ideas were very influential and became a basic reference for subsequent debates on the nature of physics theory and the relationships between theory, experiments and explicative models. By contrast, his contemporary and colleague Poisson sustained the relevance of molecular models for discovering the mechanisms producing thermal phenomena and considered mathematical equations as useful tools in order to develop the consequences of the models:

> It is matter of deducing, by rigorous calculations, all the consequences of a general hypothesis on heat communication, which is based on experience and on analogy. These consequences will be then a transformation of the same hypothesis, to which calculations do not remove nor add anything … to be complete this theory should be able to determine the movements that are provoked by heat into gases, liquids and solids … I will adopt the more fecund theory according to which these phenomena are due to a imponderable matter contained inside the parts of all bodies … this matter is called *caloric*. (Poisson 1835, pp. 5 and 7)

At the end of the nineteenth century, this debate was connected to more general philosophical debates about the role of science, materialism, realism and the relationships among science, philosophy and religion. There were widespread tendencies to dispute the autonomy of science and criticise geological and biological evolution theories. Questions were raised about whether the role of science was to provide explanations about the real world and knowledge about things existing in reality or to only develop classifications and syntheses of phenomena and observations as useful economies of thought, with explanations coming from elsewhere. Instrumentalist conceptions of science were widespread, which also rejected the atomic theories. For example, yet in 1913, Mach refused to accept the existence of atoms.

The sterility of these pure instrumentalist conceptions manifested in a resistance to accept the innovations that were emerging in physics and in not producing new results and predictions. For example, Duhem refused to accept Maxwell's electromagnetic theory, Boltzmann's statistical mechanics and Einstein's relativity and opposed Galileo's realism:

> When Kepler or Galileo declared that Astronomy has to take as hypotheses propositions the truth of which is established by Physics, this assertion … could mean that the hypotheses of Astronomy were judgments on the nature of things and on their real movements … But, taken in this sense, their assertion was false and harmful. … In spite of Kepler and of Galileo, we believe today, as did Osiander and Bellarmino, that the hypotheses of Physics are only mathematical artifices intended to *save the phenomena*. (Duhem 1908–1990, pp. 139–140)

Planck, in his treatise of 1897, offered an organic exposition of *pure thermodynamics*, as an autonomous science based on the concepts of energy and entropy and on laws independent from hypotheses about microscopic structures, avoiding the anthropomorphic ideas of degradation, dissipation and quality of energy. For example, he remarked that in an isothermal expansion of a gas, heat is integrally transformed in work, which contrasts with the idea of energy degradation. The irreversibility and the impossibility of perpetual motion became consequences of the law of entropy increase. Planck pointed out that the second law does not concern only energy dissipation and the problem of heat and work. For example, in the mixture of two gases or in the further dilution of a solution, the process does not involve changes in the type of energy but happens in a direction driven by entropy increase. According to Planck, this was the best way to deal with thermodynamics, but he specified ‘up to now’, so as not to close off possible future improvements and progress. However, thermodynamics cannot foresee nor explain some simple phenomena, such as the behaviour of the specific heat of gases, where new hypotheses on the properties of atoms and molecules will be necessary.

Currently, textbooks show very different approaches to thermodynamics (see Tarsitani and Vicentini 1996), which can be well understood only as the result of different epistemological choices. An analysis of these philosophical backgrounds is useful for students and necessary for teachers in order to choose handbooks and define course organisation.

Two ancient textbooks, having two very different approaches, have been particularly influential for the teaching of thermodynamics, those of Maxwell (1871) and of Planck (1897). The dynamical approach of Maxwell, had as background the kinetic model of heat, considered as a ‘kind of motion’. This gave a limited epistemological status to the second law, considered as a *human scale* law, not an absolute law. The phenomenological approach of Planck considered thermodynamic laws as self-sufficient laws with a broad empirical basis and a fundamental status.

For example, the well-known treatise of Zemansky (1968) develops a phenomenological approach based on the classical formulations of the three laws and on the concept of equilibrium and only in the last part is open to microscopic interpretations. By contrast, the famous Berkeley physics handbook published in five volumes does not include a volume on thermodynamics but one on *statistical physics*, thus suggesting a nonautonomous status of thermodynamics (Reif 1965; see also Reif 1999). Moreover, this handbook avoided any reference to the methodologically and philosophically problematic issues related to the topic.

Explanations proposed in thermodynamics are often unsatisfactory for the students’ need of understanding because they only show how things must be or not be, but not how things happen, by which processes and mechanisms a new situation is established. This raises questions about causal or formal laws, and correlation or necessity relationships. The idea of irreversibility is intuitive and in line with observations of daily reality, but the irreversible processes are difficult to treat mathematically. To overcome this difficulty, abstract conceptual devices which appear artificial to students are used, such as quasi-static or reversible transformations (a succession of equilibrium states: the system would remain spontaneously in every one of these states, and it can be moved to another state only by means of an external manipulation or force).

9.4.5 Stationary Situations and Dissipative Structures

The tendency to equilibrium, to uniformity and to cancellation of differences, suggested by the second law of thermodynamics, can appear to contradict the observation of phenomena of self-organisation and the spontaneous formation of ordered

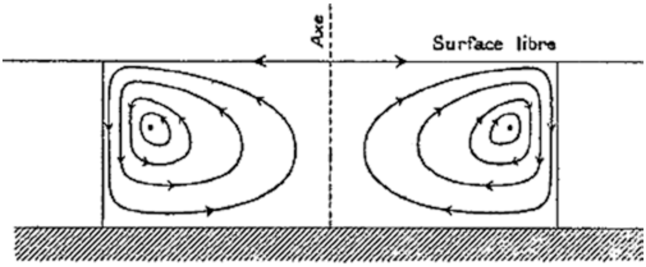

Fig. 9.3 The Bénard's cells (From Bénard 1900, p. 1005)

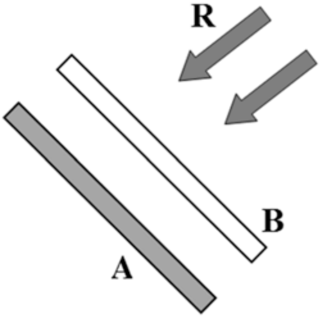

Fig. 9.4 The ideal greenhouse in the empty space. Two plates A, B, initially at same temperature, are exposed to a radiation R of short wavelength. A is black for all radiations, B is a glass which is transparent to radiation R but absorb all far infrared thermal radiation emitted by A. After a time a stationary condition is reached in which the temperature of the two plates are different: $T_A = T_B \cdot \sqrt[4]{2} \cong 1.19 T_B$

structures in nature. In this way, it is useful to study stationary situations without thermal equilibrium, in connection with the *dissipative structures* described by Prigogine, as the spontaneous creation of nonuniform structures in situations far from equilibrium. This suggests the actual possibility of spontaneous creations of ordered structures without contradicting the second law of thermodynamics.

Indeed, just the entropy flow is at the origin and sustains the nonuniformity. Examples are the spontaneous growing of a crystal in an opportune solution, the formation of regular convective cells in a layer of liquid heated from below (Bénard's cells, see Bénard 1900 and Fig. 9.3) and more generally also life. Prigogine and Stengers (1988, pp. 49–50) described an experiment showing that two different gases (nitrogen and hydrogen), initially uniformly mixed in two communicating containers kept at different temperatures, spontaneously separate from each other, more hydrogen going in the hotter container and more nitrogen in the colder one.

Other examples useful for teaching in high school classes can be a greenhouse in empty space (Fig. 9.4), the greenhouse effect on the Earth or simply a room with the heating keeping a constant difference of temperature with outside. They can be considered ordered structures in the sense that *correlations at distance between parts of the system* are created, for example, between the temperatures of the base and of the covers of a greenhouse. At the same time, the study of nonequilibrium stationary situations is important from a didactic and conceptual point of view because these situations are very common in various parts of physics and students have difficulty in understanding them and dealing with them correctly. Also the entire Earth is a system that receives solar radiation at low entropy and emits infrared radiation with higher entropy, and it is this negative entropy flux which makes it possible to create or maintain ordinate structures.

9.5 Case Histories for Teaching and Learning Thermal Phenomena and Thermodynamics

Many case histories useful for teaching can be found in the history of thermodynamics. Here I will mention some of these, which have valuable conceptual, cognitive and epistemological implications.

9.5.1 Theories on the Nature of Heat

What is heat? Since antiquity philosophers and scientists have tried to answer this question. The history of the ideas on the nature of heat is a case history which can be used at various school levels and can promote interest and motivation. Two main conceptions emerge which can be followed through the centuries, with their variations, in the scientific debates: heat is a substance which is contained inside bodies and can pass from one body to another, or it is the effect of the motion of particles constituting bodies. A mixed conception is also found, in which heat is due to the motion of particles constituting a caloric substance.

The case history can be developed by presenting excerpts of texts by some scientists chosen because they are representative of different periods and conceptions and for their importance in science history. Reading the motivations, rationales and mistakes of scientists in their own words can be a good way to reveal and discuss students' conceptions. For didactic purposes, this long history can be simplified into four periods: Greek and Roman antiquity, the seventeenth century, the affirmation of the caloric conception in the eighteenth century and the development of a modern kinetic theory in the nineteenth century. The historical problems of the distinction between heat and temperature and of the relationship between the thermal sensations and the physical properties of matter should be outlined, because they are clearly linked with common students' difficulties. Some experiments should also be described which were considered relevant in order to discriminate between different theories. I will give in the following some examples of scientists' significant quotations that can be proposed to students.

Lucretius, in the context of his atomistic philosophy and following his predecessors Democritus and Epicure, considered heat as a substance made of special atoms (in Latin, *semina ignis*, *corpuscula vaporis,* i.e. seeds or grains of fire, particles of vapour or of heat). In this excerpt, Lucretius is trying to explain why the water of a certain famous spring was colder during the day than during the night, a fact that appeared very surprising:

> These particles of heat (*corpuscula vaporis*) do not travel isolated, but they are entangled and amassed, so that each one is restrained by the others and by external bodies, and consequently they are compelled to advance more slowly. […]
>
> The earth near the spring is more porous than elsewhere, and be many the seeds of fire (*semina ignis*) near the water; on this account, when night submerges the earth, soon the earth gets chilly and contracts in its depths; and thus, as if one had squeezed it by the hand, it pushes into the spring the seeds of fire that it holds, which render warm the touch and steam of the fluid. Next, when the sun has risen with its rays and dilated the soil by mixing it with its fires, the seeds of fire again return into their previous abodes, and all the warm of water retires into the earth; and this is why the fountain in the daylight gets so cool. (Lucretius *De rerum natura* (On the Nature of Things), book II, lines 154–156 and book VI, 861–873)

During the seventeenth century, in the context of the new affirmation of mechanistic and atomistic philosophy, with the distinction between primary and secondary properties, many scientists adhered to a kinetic conception (Bacon, Descartes, Boyle, Mariotte, Hooke, Newton) or a mixed conception (Gassendi, Galileo, Boerhaave, Lemery). Galileo sustained a mixed conception:

> Those materials which produce the warm sensations … are a multitude of little particles, having various shapes and moving at different speeds … to excite the warm sensation the presence of particles of fire (*ignicoli*, in Italian), is not sufficient but also their motion is necessary, so that it can be said very rightly that motion is the cause of heat. (Galileo, *Il Saggiatore*, 1623, pp. 781 and 783)

The conception of heat as a substance spread rapidly during the eighteenth century, in connection with the more general affirmation of physical interpretations based on models of imponderable fluids (e.g. electricity, magnetism, phlogiston, ether).

Joseph Black (1728–1799) developed in a more detailed way the theory of heat as a substance, called *caloric*, and gave a strong contribution to the success of this conception. He distinguished between free and latent (or combined) caloric, and he was the first to clearly understand, around 1760, the distinction between heat and temperature and to define the physical quantities of specific heat and latent heat (nevertheless, his ideas diffused slowly only after 1770 and his *Lectures* were published only after his death in 1803):

> [In a situation of thermal equilibrium usually scientists imagined that] there is an equal quantity of heat in every equal measure of space, however filled up with different bodies. The reason they give for this opinion is that to whichever of those bodies the thermometer be applied, it points to the same degree. But this is taking a very hasty view of the subject. It is confounding the quantity of heat in different bodies with its general strength or intensity, though it is plain that these are two different things, and should always be distinguished … The quantities of heat which different kinds of matter must receive … to raise their temperature by an equal number of degrees, are not in proportion to the

> quantity of matter in each, but in proportions widely different from this, and for which no general principle or reason can yet be assigned… different bodies, although they be … of the same weight, when they are reduced to the same temperature or degree of heat, … may contain very different quantities of the matter of heat. (Black 1803)

At that time, there was confusion between temperature and heat, and temperature was considered as a measure of intensity, strength, density, level or degree of heat. Newton wrote of 'degree of heat', measured by a thermometer. These ideas are clearly similar to some widespread students' conceptions (see Sect. 9.2).

During the period between the last decades of the eighteenth century and the beginning of the nineteenth century, scientists were divided and uncertain on this problem. It can be interesting to show how the opinion of a same scientist changed over some years. For example, this is shown by these two quotations of Lavoisier:

> It is difficult to understand these phenomena without admitting that they are the effect of a real and material substance, of a very subtle fluid, which insinuates among the molecules of all bodies. (Lavoisier 1789, p. 19)

> Physicists are divided about the nature of heat. Many of them consider it as a fluid diffused in all the nature… others think that it is the result of the insensible motion of molecules of matter … We will not decide between the two hypotheses. (Lavoisier and Laplace 1780, pp. 357–358)

By contrast, Alessandro Volta in 1783, in his *Memoria intorno al calore* (Memory on Heat), was very sure 'That heat is a peculiar element, distinct from all other substances, seems to us not a probable opinion but an indubitably established truth'.

Things changed notably with the works of H. Davy (1799) and of B. Thomson-Rumford:

> I cannot refrain from just observing that it appears to me to be extremely difficult to reconcile the results of any of the foregoing experiments with the hypothesis of modern chemists respecting the *materiality of heat* … There are many appearances which seem to indicate that the constituent particles of all bodies are also impressed with continual motions among themselves, and that it is these motions (which are capable of augmentation and diminution) that constitute the *heat* or temperature of sensible bodies. (Thomson-Rumford 1804, pp. 103–104)

Nevertheless, during the same years Dalton was of the opposite opinion:

> The most probable opinion concerning the nature of caloric is that of its being an elastic fluid of great subtlety, the particles of which repel one another, but are attracted by all other bodies. (Dalton 1808, p. 1)

Dalton developed an explicit analogy between heat contained in a body and a liquid in a vessel in order to help clarify the concepts of specific and latent heat and of temperature (De Berg 2008, proposed the use of similar historical analogies for teaching; see Sect. 9.3 and Fig. 9.1).

Finally, the concept of heat became clear after the discovery of energy conservation, as this excerpt from Maxwell shows:

> The temperature of a medium is measured by the average kinetic energy of translation of a single molecule of the medium … The peculiarity of the motion called heat is that it is perfectly irregular; that is to say, that the direction and magnitude of the velocity of a molecule at

> a given time cannot be expressed as depending on the present position of the molecule and the time. (Maxwell 1875, p. 376)

This history offers many elements which can be developed in a way suitable for teaching. For example (see Sect. 9.3), Conant (1957) proposed a case history on the rise and decline of the caloric theory including Black's discoveries and the experiments of Davy and Rumford on the heat produced by friction, and Stinner et al. (2003) proposed a 'mini-confrontation' between Rumford and the sustainers of caloric theory.

9.5.2 The Discovery of Radiant Heat, the Debate on Its Nature and the Search for the Law of Thermal Radiation

The first studies on radiant heat began in the seventeenth century (see Cornell 1936). The existence of invisible heat rays that can be concentrated by using mirrors was proven by F. Bacon (1620, Book two, XII). Experiments realising the separation of radiant heat from light by glass were performed by E. Mariotte (1679) and confirmed by R. Hooke (1682). Newton himself suggested ether vibrations as a way of heat propagation and described some experiments on heat transmission in a vacuum:

> Is not the Heat of the warm Room conveyed through the *Vacuum* by the Vibrations of a much subtler Medium than Air, which after the Air was drawn out remained in the *Vacuum*? … And do not hot Bodies communicate their Heat to contiguous cold ones, by the Vibrations of this Medium propagated from them into the cold ones? (Newton, *Optiks*, 1712, Query 18)

The first systematic experiments distinguishing the different properties of light, radiant heat and heat convection were described by C.W. Scheele (1777), who also introduced the term 'radiant heat'. Other terms used were 'invisible heat', 'obscure heat', 'free heat' or 'free fire'. In 1790 M-A. Pictet wrote that 'free fire is an invisible emanation which moves according to certain laws and with a certain velocity'. P. Prévost (1791) sustained that 'free radiant heat is a very rare fluid, the particles of which almost never collide with one another and do not disturb sensibly their mutual movements' (translated in Brace 1901, p. 5). J. Hutton (1794) suggested that it was an 'invisible light … which can be reflected by metallic surfaces, and which has great power in exiting heat' (pp. 86–88). In 1800, W. Herschel discovered infrared radiation in the solar spectrum. After 1800, the existence of invisible radiant heat was well established and clearly distinguished from heat conduction, but the debate about the nature of radiant heat would continue for decades, in particular its relation with light, whether they have an identical or a distinct nature.

Later, research concentrated on the search for the laws of thermal radiation. The experiments of Delaroche (1812), which are interesting for teaching, showed that there is not a linear dependence on the temperature difference ('The quantity of heat which a hot body yields in a given time by radiation to a cold body situated at a distance, increases, *caeteris paribus*, in a greater ratio than the excess of temperature of the first body above the second'), so opening the search for a correct relationship. Biot (1816) proposed a mathematical formula containing a cubic term, and Dulong and Petit (1817) found an exponential formula $F(T) \propto a^T + const$. It is important to stress that it was impossible to find a correct law for thermal radiation without using an opportune temperature scale with an absolute zero, like that introduced by Kelvin in 1848. Only in 1879 did Josef Stefan, starting from the experimental measurements of Tyndall, propose the famous empirical relationship asserting that the total radiant energy emitted by a black body per unit time is proportional to the fourth power of the absolute temperature of the body.

Stefan's formula was not immediately accepted by the scientific community, until Ludwig Boltzmann derived it theoretically in two articles published in 1884, based on the previous works of Bartoli. The theoretical reasoning and the thought experiments of Bartoli and Boltzmann constituted a meeting point between thermodynamics, electromagnetism and thermal phenomena, where thermal radiation was treated as a gas to which thermodynamic transformations could be applied with changes of pressure and volume. This raised questions about the extent to which this treatment is lawful and what it means from the point of view of thermodynamics and of the nature of thermal radiation and from the point of view of epistemological reductionism.

This case history is interesting, because it highlights the difficult and tortuous process of discovery, delimitation and differentiation of a new phenomenon, in this case the differentiation of thermal radiation from heat conduction and the understanding that it is a phenomenon of the same nature as light, an apparently very different phenomenon. Moreover, it can show how knowledge in physics does not arise from the simple observation of phenomena as they appear, the ordering and classification of data and simplified descriptions. Rather, it implies a conceptual reconstruction of complex experimental fields, the definition of structures, properties and mechanisms producing and explaining phenomena and allowing previsions and hypotheses about new phenomena.

9.5.3 The Caloric and Frigorific Rays in Thermal Radiation

The ideas of frigorific rays and of reflection and focusing of cold were put forward by G. Della Porta (1589) and confirmed by the *Accademia del Cimento* of Florence in Italy (1667). In contrast, Marc-Auguste Pictet, Pierre Prévost and other proponents of the material nature of heat interpreted these phenomena as a result of a peculiar arrangement of caloric transmission. An interesting controversy took place between Rumford and Prévost about the existence of cold radiation and the nature of heat (see Chang 2002). Rumford considered the existence of frigorific radiation as a strong argument against the caloric theory. He considered that both calorific and frigorific radiations exist in the sense that the radiation emitted by a body will have a heating effect on a colder body and a cooling effect on a warmer body. He considered this latter as a real effect, due to the undulations of lower

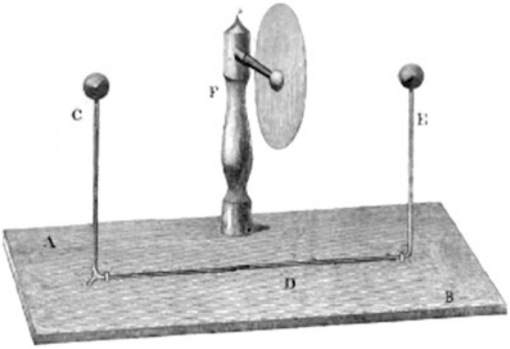

Fig. 9.5 The Rumford's thermoscope (Thomson-Rumford 1804, p. 30). "A small *bubble* of the spirit of wine … is now made to pass out of the short tube into the long connecting tube; and the operation is so managed that this bubble (which is about ¾ of an inch in length) remains stationary, at or near the middle of the horizontal part of the tube, *when the temperature (and consequently the elasticity) of the air in the two balls, at the two extremities of the tube, is precisely the same*." (p. 48). The heating or cooling of only one of the balls forces the alcohol bubble "to move out of its place and to take its station nearer to the colder ball" (p. 49). "The result of the foregoing experiment appeared to me to afford the most indisputable proof of the radiation of cold bodies, and that the rays which proceed from them have a power of generating cold in warmer bodies which are exposed to their influence" (p. 61)

frequency, which produce a deceleration of the particle's vibration of the warmer body that they invest:

> The result of the foregoing experiment appeared to me to afford the most indisputable proof of the radiation of cold bodies, and that the rays which proceed from them have a power of generating cold in warmer bodies which are exposed to their influence … I have discovered, first, that all bodies at all temperatures (cold bodies as well as warm ones) emit continually from their surfaces rays, or rather, as I believe, *undulations*, similar to the undulations which sonorous bodies send out into the air in all directions, and that these rays or undulations influence and change, little by little, the temperature of all bodies upon which they fall without being reflected, in case the bodies upon which they fall are either warmer or colder than the body from the surface of which the rays or undulations proceed. … Those bodies which, when warm, give off many calorific rays would, when colder than the surrounding objects, give off to them many frigorific rays … the frigorific influences of cold bodies have always appeared as real and effective as the calorific influences of warm bodies. (Thomson-Rumford 1804, pp. 61 and 178–179)

Rumford described experiments performed using a special instrument, the *thermoscope* (see Fig. 9.5), which are interesting for teaching purposes because they are simple in their empirical description but can be differently interpreted, and show that it is not obvious to contrast the interpretation based on the idea of frigorific rays, which we currently consider erroneous. Moreover, these experiments can be a useful example for teaching some themes on the nature of science (NOS), as they stimulate a debate among students with different possible interpretations and raise the issue of the possibility of non-conclusive results of experiments regarding a choice between different theories.

9.5.4 *The Discovery of the Second Law of Thermodynamics and the Invention of Entropy*

This historical theme is useful to clarify the various meanings of the second law, by following and exploring the statements of Kelvin, Clausius and others, the relationships with energy conservation and Carnot's theory and the development of entropy interpretations (Clausius, Boltzmann, Gibbs and the informational entropy). An example of direct utilisation in teaching of excerpts from Carnot, Clausius and Boltzmann is given by Viard (2005) (see Sect. 9.3).

As previously pointed out in Sect. 9.4.1, there was difference between Kelvin's and Clausius' approaches. Kelvin referred to useful work, energy waste or dissipation and degradation of energy:

> There is an absolute waste of mechanical energy available to man when heat is allowed to pass from one body to another at a lower temperature … As it is most certain that Creative Power alone can either call into existence or annihilate mechanical energy, the 'waste' referred to cannot be annihilation, but must be some transformation of energy … The following propositions are laid down regarding the *dissipation* of mechanical energy from a given store, and the *restoration* of it to its primitive condition. They are necessary consequences of the axiom, '*It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects*'. (Thomson-Kelvin 1852, p. 305)

Clausius' formulation of the second law evolved from a measure of the equivalence value of transformations and the law of nonnegative value of a cycle (1854) towards the concept of *disgregation* and the nonnegative value of disgregation for all transformations (1862, 1867, 'introducing a new magnitude, which we call the *disgregation* of the body, and by help of which we can define the effect of heat as simply *tending to increase the disgregation*') and eventually to the concept of entropy (1865, 1867, 'we might call *S* the transformational content of the body … I propose to call the magnitude *S* the *entropy* of the body, from the Greek word tropè, *transformation*'). This led to the two very general sentences: 'The energy of universe remains constant' and 'The entropy of the universe tends to a maximum'. If the universe reached the state of maximum entropy, all energy would be uniformly diffused throughout space at a uniform temperature. Consequently, no mechanical work could be done, no transformations could happen and life would cease to exist; it is the 'heat death'.

The idea of useful work was resumed by Gibbs in a more rigorous manner, by defining the quantities available work and *free energy* and connecting them with entropy. Later on, similar ideas were developed in a new way, in the context of the problems of energy saving and environmental issues. A new quantity *exergy* was defined (the term was coined by Z. Rant in 1956), which is dimensionally homogeneous to energy but it is not conserved and equals the maximum work that can be provided by a system as it proceeds to its final state in thermodynamic equilibrium with the environment.

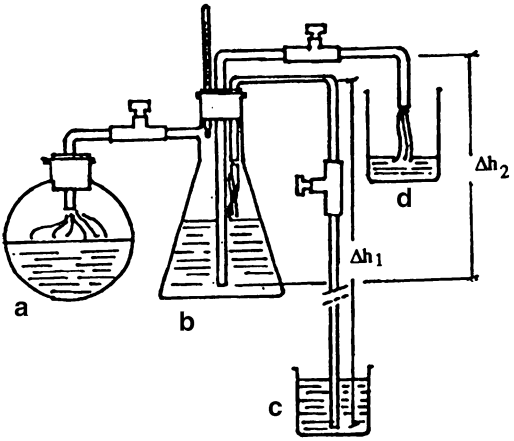

Fig. 9.6 A didactical experiment reproducing the essential features of Savery's steam engine (From De Filippo and Mayer 1991, p. 121). A is the boiler, B the cylinder, C is the well from which the water must be raised (the mine, in the original historical utilization), and D is the upper water tank

9.5.5 The History of Steam Engines

The history of steam engines, from precursors such as Branca, Desaguliers and Papin to the first useful practical realisations of Savery, Newcomen and Watt, is a case which allows an exploration of the problem of relationships between science, technology and society (see Cardwell 1971). The connections can be usefully demonstrated with the general background of the development of industry and the industrial revolution in England and the practical and productive problems that the new engines aimed to solve (a didactic presentation of this history is given in the *Project Physics Course* 1970 and in Brenni et al. 2009; see Sect. 9.3). More specifically, the connections can be studied by looking at the improvement of water pumps, the engines' efficiency and Watt's innovations. The introduction of a separate cold condenser allowed dramatic improvements in power and efficiency, and Watt's centrifugal governor, the first automatic feedback control device, precursor of others, represented a significant advancement in technology since the feedback loop allowed the steam engine to be self-regulating.

A didactic experiment reproducing the essential features of Savery's engine (1699) can be proposed (see Baracca and Besson 1990; De Filippo and Mayer 1991 and Fig. 9.6). The study can usefully prosecute with the introduction of the more recent concept of the *second-order efficiency* or *exergetic efficiency* of a thermodynamic process, defined as the ratio between the desired exergy output and the exergy input used (Viglietta 1990). In the context of the education to sustainable development, this concept is a useful instrument to evaluate the appropriate use of energy sources and the environmental effects of technological devices.

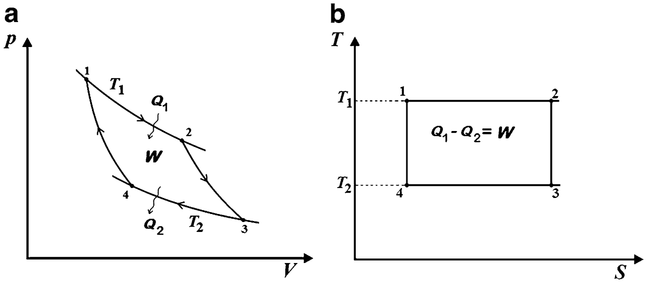

Fig. 9.7 The Carnot cycle represented (**a**) in a pressure-volume graph and (**b**) in a temperature-entropy graph

9.5.6 The Carnot Cycle, Caloric and Entropy

The Carnot cycle is often badly understood by students as it appears to be a strange object in the study of thermodynamics. Students may be confused about why there is just a cycle with an isotherm and an adiabatic process (Fig. 9.7a), this last being more complicated to deal with mathematically. They may also wonder whether the obtained conclusions are valid only for this strange type of cycle or for any cycle. The cycle diagram is difficult to understand for students and the choice of adiabatic and isotherm transformations remains obscure.

In fact, the Carnot cycle (1824), subsequently resumed by Clapeyron (1834), was born in the context of a theory of heat as a fluid, the caloric, which is conserved during the operation of a thermal engine. It makes clearer sense with reference to this theory, as a coupling of transformations keeping constant one of the two fundamental quantities, heat or temperature. The work would be produced by the passage of a given amount of heat from a higher temperature to a lower temperature and is a by-product of the movement of heat, in an analogy with hydraulic engines:

> The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. (Carnot 1824–1897, p. 61)

The Carnot cycle makes sense inside a history that has its precedent in the study of hydraulic engines and their efficiency (Lazare Carnot and John Smeaton). It was with reference to them that Sadi Carnot studied the problem of the efficiency of thermal engines by using an analogy between caloric fluid and water. Subsequently, the problem arose of reconciling Carnot's results with the heat-work equivalence, demonstrated by Joule and others, an issue which preoccupied Kelvin. Is it the falling of caloric to a lower temperature that produces work or is a part of heat transformed in work, respecting energy conservation? The theory of heat was changed; heat was no longer considered to be a substance which is conserved, but the importance of the Carnot cycle remained, despite its change in meaning. It became a start point for discovering the second law of thermodynamics and also for the definition of Kelvin's absolute temperature.

In fact, the Carnot cycle remained for decades at the middle of the conceptual development of thermodynamics as a thread, a reference and a problem and also perhaps as an obstacle, which, because of the generality and the theoretical strength of its conclusions, may have withheld thermodynamics for a long time around issues and discourses related to reversible cycles and thermal engines.

In this way an analysis of the cycle from a historical point of view, starting from the original interpretation of Carnot and Clapeyron in the framework of the caloric theory and prosecuted with a revised and modified treatment, can be useful in encouraging a better and deeper understanding and can activate a debate on the meaning of heat and reversibility (see Newburgh 2009).

Carnot introduced the idea of the maximum theoretical efficiency of a thermal engine, depending only on the considered temperatures. The work obtained is proportional to the heat taken and to the temperature difference. In the hydraulic engines the work is also proportional to the water mass and to the height difference. However, differently from hydraulic engines, in a thermal engine the work depends also on the absolute value of temperatures, not only on the temperature difference, and increases for lower temperatures. ('The fall of caloric produces more motive power at inferior than at superior temperatures', Carnot 1824–1897, p. 97). According to Carnot, this fundamental property is strictly linked with the hypothesis, supported by the experiments of F. Delaroche and J. E. Bérard, that the specific heat of a gas increases with volume (p. 40), a property that was explained by using the difference between free and combined heat.

Consequently, in the theory of Carnot-Clapeyron, the obtained work W is proportional to heat Q and to temperature difference $\Delta T = T_1 - T_2$, $W = \mathrm{C} \cdot Q \cdot \Delta T$, but it depends also on T_2 and it increases with diminishing T_2. The proportionality coefficient C (called Carnot function) can be taken as a measure of the inverse of the temperature $1/T$ ('we may define temperature simply as the reciprocal of Carnot function', Joule and Thomson 1854, p. 351) and then $W = Q \cdot \Delta T / T_2$. Leaving the caloric theory and passing to the modern conception, for the energy conservation it is $Q_1 \neq Q_2$ and $W = Q_1 - Q_2$ and therefore the proportionality is obtained $Q_1/T_1 = Q_2/T_2$. It is interesting that Carnot referred to an absolute zero temperature that he assumed to be −267 °C, on the basis of data on the gases behaviour, so he always wrote in his formulas $(t + 267)$, t being the Celsius temperature.

Carnot did not draw graphs, whilst Clapeyron drew the well-known volume-pressure diagrams (Fig. 9.7a). In the framework of the caloric theory, in a heat-temperature diagram the graph of the cycle would be simply a rectangle. This type of graph is not acceptable in the current theory according to which heat represents transferred energy and is not a state function. Nevertheless, by modifying the quantity on the abscissa from Q to Q/T, the diagram becomes correct and meaningful from the modern point of view: the obtained graph is still a rectangle (Fig. 9.7b) and the axis of the abscissa now indicates a new state quantity, which is entropy S. Furthermore, being $Q = T\Delta S$ for reversible processes, the area of the rectangle is equal to $Q_1 - Q_2$ and therefore is equal to the obtained work W.

9.5.7 The Cooling Law and the Definition of a Temperature Scale: From Newton to Dalton

Research on the cooling law of objects in a colder environment began with Newton's article published in 1701. Later, numerous studies were conducted by other scientists, confirming or confuting Newton's law (Besson 2012). These studies were connected with the problem of defining a good scale of temperatures, a connection which was dealt with in Newton's article and in Dalton's work published in 1808.

This historical subject is interesting for its epistemological implications and its possible utilisation in teaching. It involves concepts and phenomena that are usually covered in normal courses but about which there exist many difficulties and erroneous conceptions. The cooling law uses mathematical tools that can be easily understood by students, and simple experiments suitable for a school replication (e.g. Metz and Stinner (2006) developed teaching activities centred on the replication of some experiments of Rumford on cooling process; see Sect. 9.3). Moreover, it allows the treatment of various methodological issues, such as the relationship between experimental data and mathematical models, the role of philosophical ideas of scientists and the definition of quantities such as temperature that need a progressive construction from simple observations towards general properties and laws.

In 1701, Isaac Newton published a short article in which he provided a table of temperatures and established a relationship between the temperatures T and the time t in cooling processes. He did not write any formula but expressed his cooling law verbally: 'The excess of the degrees of the heat … are in geometrical progression when the times are in an arithmetical progression'. By reading his text, it is hard to sustain that Newton was discovering experimentally an exponential law of cooling. He was mainly interested in defining a thermometric scale for high temperatures (*scala graduum caloris*). Newton did not consider the exponential law of cooling as an experimental result but as a general hypothesis, which allows a temperature scale to be built. He found the temperatures by using two different methods, one based on the property of thermal dilatation of linseed oil and the other based on the cooling time of a piece of iron. Newton considered his cooling law as a general property of heat.

Later, faced with the discrepancies between the cooling law and experiments, scientists assumed different attitudes. Some scientists (Martine, Erxleben, Delaroche, Biot, Dulong and Petit) assumed an empiricist attitude, concluding that Newton's cooling law was not entirely true, and looked for new different laws. Other scientists tried to keep the simple remarkable law, by considering the effect of disturbance factors (e.g. Richmann, Prévost, Leslie) or by revising the common temperature scales in order to reobtain the agreement between theory and experiments (e.g. Rumford, Dalton). Still in 1804, Leslie wrote:

> It is *assumed* as a *general principle*, that the decrements of heat are proportional to the difference of temperature of the conterminous surfaces. On this supposition, the successive temperatures of a substance exposed to cool, would, at equal periods, form a descending geometrical progression. (Leslie 1804, pp. 263–264)

John Dalton (1808) remarked that the exponential law of cooling was not exactly valid if the common [Fahrenheit] thermometric scale was used ('one remarkable trait of temperature derived from experiments on the heating and cooling of bodies, which does not accord with the received scale, and which, nevertheless, claims special consideration'). He then defined a new scale of temperatures, which would allow the law to remain valid together with three other simple physical laws concerning the thermal dilatation of liquids and of gases and the change with temperature of steam pressure. The agreement that he found or believed he had found (his experimental data were not so accurate and ample, especially at high temperatures) among four simple laws of four different phenomena was for him a strong clue that a fundamental property of heat had been found, connected to the new temperature scale.

This epistemological attitude is similar to that of Newton (in his *Principia* Book 1, Section 1, Scholium), when he distinguished between absolute, true, mathematical time and relative, apparent, common time. Similarly, a distinction can be conceived between the true, mathematical temperature, which responds to exact general laws, and a sensible, apparent temperature, measured by material devices. Scientists try to find the best realisation of the true temperature. In a sense, the current definition of thermodynamic temperature can be considered as a successful finding of this search. But for a time, many scientists thought too easily that they were finding exact general laws, confirming the human tendency of attributing more order and regularity to things than actually observed, a tendency that F. Bacon (1620) pointed out as one of *idola tribus* hindering the formation of correct knowledge.

Dulong and Petit (1817) criticised Dalton because 'he unduly hastened to generalize some outlines … which were based only on dubious evaluations'. They performed a very accurate experimental study, considering a temperature scale based on the air thermometer, and distinguished cooling processes due to radiation and to convection, by measuring the cooling velocity of a body in a vacuum due to 'the excess of its own emitted radiation over that of the surrounding bodies'.

This *case history* offers the occasion for teaching various epistemological and methodological issues, as, for example:

- The relationship between experimental data and mathematical models, the problem of the field of validity of empirical laws and the interpretation of discrepancies between laws and experimental data, either as the effect of errors and disturbance factors or as a clue that the law is not valid
- The role of philosophical ideas and preferences of scientists in their scientific research, for example, the faith in the simplicity of natural laws or the confidence in the existence of a unique law and a sole cause for an empirical phenomenon
- The definition of quantities such as temperature, which cannot be defined simply by means of a sentence such as 'temperature is…' but need a progressive construction starting from thermal sensations towards the choice of thermometric substances and quantities, and the search for a universal property independent from a specific substance

9.5.8 *The Construction of the Physical Quantity Temperature*

As pointed out in the previous Sect. 9.5.7, temperature is a quantity which cannot be simply defined by a sentence or a formula but needs a progressive construction. The historical path of this scientific construction (see Chang 2004) can be adapted for building a case history which usefully parallels and accompanies the students' learning progression from subjective warm-cold sensations towards the specification of body properties, such as dilatation or pressure, which depend on being colder or warmer, and the successive generalisations leading to absolute thermometer scales that are independent of specific materials (examples of didactic use of this case are given by Mäntylä and Koponen (2007) and Oversby (2009); see Sect. 9.3).

Also the research about an absolute zero of temperature offers an interesting historical thread which does not demand very difficult mathematical and conceptual tools, and it is suitable for high school students. Already Amontons, at the beginning of the eighteenth century, proposed the idea of an absolute zero of temperature based on the gas law, i.e. the temperature at which gas pressure is zero, and following this definition Carnot calculated the absolute zero at −267 °C. Dalton (1808) used different phenomena and reasoning (see Besson 2011) for finding the 'natural zero of temperature' which he considered as a state of 'absolute privation of heat':

> If we suppose a body at the ordinary temperature to contain a given quantity of heat, like a vessel contains a given quantity of water, it is plain that by abstracting successively small equal portions, the body would finally be exhausted of the fluid. (Dalton 1808, p. 82)

Based on his experiments and calculations, he concluded that it was correct 'to consider the natural zero of temperature as being about 6,000° below the temperature of freezing water, according to the divisions of Fahrenheit's scale' (p. 97). In contrast, by studying the cooling law in a vacuum due to radiation, Dulong and Petit (1817, p. 259) concluded that the absolute zero should be at infinite degrees below 0 °C. Moreover, the absolute thermodynamic temperature can be introduced as a result of Kelvin's reflections on Carnot's work:

> If any substance whatever, subjected to a perfectly reversible cycle of operations, takes in heat only in a locality kept at a uniform temperature, and emits heat only in another locality kept at a uniform temperature, the temperatures of these localities are proportional to the quantities of heat taken in or emitted at them in a complete cycle of operations. (Joule and Thomson 1854, p. 351)

9.6 Conclusion

The richness of the above-outlined examples of philosophical problems, case histories, multidisciplinary themes and issues involving technological, social and cultural contexts shows the numerous possibilities of the use of history and philosophy of science in teaching thermal phenomena and thermodynamics. As it has been shown, many research examples can be found in the research literature on this problem.

Matthews (1994, pp. 70–71) indicated three ways in which the history of science can be and has been included in science programmes: the add-on approach (minimalist, where units on the histories of science are added on to a standard nonhistorical science course), the integrated approach (maximalist, organising a whole science course on historical grounds) and the storyline approach (using history in order to create a storyline for the science content, where the subject matter is embedded in a historical matrix and history 'provides the framework onto which a science topic or whole course can be placed in a developing narrative').

The integrated, maximalist, approach needs strong multidisciplinary organisation and appropriate teacher training. Moreover, teachers may be unwilling to adopt a whole new course based on a historical approach because it can be too demanding for them. However, they may be more willing to insert new short units in their existing course. In this way, research could usefully focus on the development and testing of a number of such new teaching units, which include new complementary materials in the various forms considered above (narratives, experiments, historical dramas, controversies, cases, debates …) and making a didactic transposition of historical and philosophical problems.

Concerning thermodynamics, new teaching units could be developed around the philosophical and historical themes briefly outlined in Sects. 9.4 and 9.5. Moreover, two particular problems merit a mention here. The first one concerns the difficulty of teaching the entropy concept at high school level, and indeed most teachers and handbooks avoid it or refer to it in a vague and imprecise way, often with inaccurate statements. A research problem is whether and how a historical approach could provide a learning path in which a discussion of different approaches that were developed by scientists in the past and the controversies that arose can foster a better understanding of physical concepts and a deeper awareness of the cultural context and implications related to this issue.

The second problem refers to the special connections of thermodynamics with historical, technological and economic problems, whose echoes are embedded in the core of the structure and language of thermodynamics, involving thermal engines, efficiency, work, etc. For example, it is hard to avoid any reference to the connection between the meanings of the word 'work' in the scientific language and in common language. A discussion of the historical origin of this apparently strange choice should be taken into account rather than disregarded, as it usually is in textbooks. A challenge is how to develop teaching courses and materials taking into account these aspects and giving meaning and historical background to these concepts and terminologies, without structuring a whole reorganisation of the course on historical grounds.

A more general problem seems to be how to fill the gap between didactic research and actual school practice. In this field, research products are too often limited to historical and/or philosophical analysis with some interesting but generic pedagogical suggestions for teaching. More studies are needed which have to be specifically designed, tested and evaluated for school classes, including materials for students and teacher guides. The role of teachers is decisive: on one hand, research proposals must take into account more clearly the teachers' needs; on the other hand, new programmes of teacher education should be designed and developed, and teachers should become able to find, adapt and utilise resources produced by science education research. These problems also demand research and projects concerning university science courses, which are too focused on technical and algorithmic knowledge and skills, and disregard conceptual, problematic and cultural aspects needed not only for future teachers but also for general and professional faculties.

Moreover, for studies in this field to produce interesting cognitive results and significant practical effects on actual school teaching, collaboration is needed in a research team among researchers in history and/or philosophy of science, researchers in science education and school teachers.

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Part II
Pedagogical Studies: Chemistry

Chapter 10
Philosophy of Chemistry in Chemical Education: Recent Trends and Future Directions

Sibel Erduran and Ebru Z. Mugaloglu

10.1 Introduction

Traditionally, chemistry had minimal existence within philosophy of science as Good (1999) explains:

> One of the characteristics of chemists is, that most have no interest in the philosophy of science…The disinterest appears to work in both directions. Modern philosophers very seldom give even a passing mention to modern chemical issues (Michael Polanyi and Rom Harré are among the few exceptions I know of). Recently, a few philosophers have attempted to discuss 'scientific practice'; but generally they have not included *chemical* practice. It is as if philosophers have believed that the way physics is 'done' was the way that all science is, or should be, done. (Physicists, no doubt, are the source of this opinion.) (Good 1999, pp. 65–66)

The disinterest in the philosophical aspects of chemistry by philosophers, chemists and educators mirrors earlier observations about a similar lack of interest regarding history of chemistry:

> Chemists, compared with other scientists, have relatively little interest in the history of their own subject. This situation is reflected, and perpetuated, by the antihistorical character of most chemical education. (Stephen Brush quoted by Kauffman 1989, p. 81)

Since the mid-1990s however, there has been an upsurge of interest in the study of chemistry from a philosophical perspective.[1] An increasing number of books, journals, conferences and associations focused on the articulation of how chemistry

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[1] See, for instance, Bhushan and Rosenfeld (2000), Chalmers (2010), Hendry (2012), Scerri (2008, 2000, 1997), Schummer (2006), van Brakel (2000), Weisberg (2006), and Woody (2004a, b, 2000), Woody et al. (2011).

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could be understood from a philosophical perspective (McIntyre and Scerri 1997; Scerri 1997; Stanford Dictionary of Philosophy 2012; Van Brakel 1997, 2010 and Baird et al. 2006). Consider, for instance, the now established *International Society for the Philosophy of Chemistry* which has recently held a symposium in Leuven, Belgium. Journals such as *HYLE* and *Foundations of Chemistry* have focused exclusively on the philosophical investigations on chemistry. Books such as Eric Scerri's *The Periodic Table: Its Story and Its Significance* have been published that provide collections that interrogate chemistry from a philosophical perspective (Scerri 2007). The *Stanford Dictionary of Philosophy* has included an entry on philosophy of chemistry (Weisberg et al. 2011).

Unfortunately the same dynamism of scholarship cannot be attributed to the infusion of philosophy of chemistry in chemical education research and practice. The development of new perspectives on how philosophical aspects of chemistry can inform education has had rather slow progress. In *Chemical Education: Towards Research-Based Practice,* Gilbert and colleagues (2003) noted that research on chemical education drawing perspectives from philosophy of chemistry represented 'research aimed at generating new knowledge, the impact of which on practice is uncertain, diffuse or long-term' (p. 398). *Science & Education* was one of first journals to dedicate space to the work of educators preoccupied with the synthesis of perspectives from philosophy of chemistry for application in chemical education (e.g. Erduran 2001, 2005, 2007). A recent edition consisting of 17 paper contributions from philosophers, chemists and educators (Erduran 2013) is testament to the journal's vision in pushing boundaries for innovative scholarship, and it illustrates the small but growing interest in capitalising on the philosophical aspects of chemistry for the improvement of chemical education.

In this chapter, some recent developments within philosophy of chemistry are outlined, and their applications in chemical education research and practice are explored. As educators, the authors' emphasis will be on the characterisation of perspectives, approaches and tools that might be offered by philosophy of chemistry for the improvement of chemical education. The goal is to explore the contributions of philosophy of chemistry in chemical education while also being mindful of how chemical education research could provide useful recommendations for the study of chemistry from a philosophical perspective. It is through such reciprocal interactions between philosophical and educational considerations of chemistry that we believe the theoretical and empirical coherence between these fields will be established.

The discussion will begin with an illustration of some key debates in philosophy of chemistry. This section will include themes such as reductionism (e.g. Scerri 1991) and supervenience (e.g. Papineau 1995) as well as aspects of chemical knowledge such as laws (e.g. Christie and Christie 2000), models (e.g. Woody 2013) and explanations (e.g. Hendry 2010). Second, the implications of these themes for chemical education research and practice will be visited. We will argue that to develop an understanding of how chemistry is conceptualised and how chemistry is learned, chemical education research has to be informed by the debates about the epistemology and ontology of chemistry. The discussion will be contextualised in the area of nature of science (NOS) that has been one of the highly studied area of research in science education (Chang et al. 2010). The contributions of how philosophy of chemistry can contribute to the characterisation of NOS by nuanced perspectives on the nature of chemistry will be discussed. Theoretical perspectives and empirical studies on NOS have tended to focus on domain-general aspects of scientific knowledge with limited understanding of domain-specific ways of thinking. NOS literature can be further developed both theoretically and empirically, thereby contributing further to HPS studies in science education. Third, some applications of philosophy of chemistry in chemical education will be outlined in more detail. Proposed frameworks for secondary and tertiary chemical education, including the context of the teaching of periodic law through argumentation (e.g. Erduran 2007), will be exemplified. Fourth, the central argument is that there is developing potential for reciprocal interplay between philosophy of chemistry and chemical education. While philosophy of chemistry can influence chemistry education, chemistry education in turn can potentially influence philosophy of chemistry, particularly in relation to empirical foundations of chemical reasoning. The chapter will conclude with some recommendations on the future directions of research in chemical education that is informed by philosophy of chemistry.

10.2 Perspectives from Philosophy of Chemistry: Some Relevant Examples for Education

Since its formalisation with its exclusive associations, books and journals, philosophy of chemistry has been preoccupied with numerous issues. It is beyond the scope of this chapter to provide an exhausted survey of the key philosophical concerns that have been raised by experts in the field. This task is left to the philosophers themselves. As educational researchers, the authors are interested in understanding some of the key debates so as to extend educators' disciplinary understanding of chemistry from a philosophical perspective and ultimately to inform educators' treatise of chemical education in a way that is informed by and is consistent with the nature of chemistry as illustrated by epistemological and ontological accounts of chemistry. In this section, some key themes will be raised that have taken centre stage in philosophy of chemistry in recent years. They are intended to highlight some central themes from philosophy of chemistry such as reductionism and supervenience which have been quite critical in the very formulation of philosophy of chemistry at its inception. The significance of these themes for chemical education will be reviewed. Subsequently attention will be devoted to a discussion on the nature of chemical knowledge, particularly in the context of explanations, models and laws. Since school curricula already aim to communicate these features of chemical knowledge in the classroom, it is entirely appropriate to complement our notions of these concepts with philosophical perspectives. Finally, the notion of chemistry as language will be visited. Considering the great deal of interest in educational research in recent years on the role of talk, discourse and language in learning (e.g. Erduran and Jimenez-Aleixandre 2008, 2012; Lemke 1990; Vygotsky 1978), this reference will seek to understand how the philosophers' approach to the role of chemical language could inform chemical education.

10.2.1 Reduction

Reduction has been a subject of debate within philosophy of science for a long time (Nagel 1961; Primas 1983). The classic view of reduction is given by Ernest Nagel in his book *Structure of Science: Problems in the Logic of Scientific Explanation* (Nagel 1961). Nagel's definition of reduction involves the axiomatisation of two theories and an examination of whether certain formal relationships exist between the axiomatised versions of these theories. A key contributor to philosophy of chemistry, van Brakel (2000) distinguished between three types of reduction. *Constitutional reduction* concerns the question of whether two domains, B and S, are ontologically identical, i.e. whether the S-entities are constituted of the same elementary substates with the same elementary interactions as B-entities. *Epistemological reduction* concerns whether the concepts (properties, natural kinds) necessary for the description of S can be redefined in an extensionally equivalent way by the concepts of B and whether the laws governing S can be derived from those of B. *Explanatory reduction* concerns the question of whether for every event or process in S there is some mechanism belonging to B which causally explains the event or the process. Furthermore, *ontological reduction* can be contrasted with *epistemological reduction*. Scerri and McIntyre (1997) have argued that even though chemistry is widely considered to be ontologically reducible to physics, the epistemological reduction of chemistry to physics is a contentious issue. Epistemological reduction would question whether or not our current description of chemistry can be reduced to our most fundamental current descriptions of physics, namely, quantum mechanics and its explanatory consequences. Scerri and McIntyre argue that it is not clear that the laws of chemistry, if they indeed exist, can be axiomatised in the first place, let alone derived across disciplines. Mario Bunge has eloquently argued that such concepts as chemical composition are necessarily 'chemical concepts' which cannot be reduced to physical explanations:

> At first sight, chemistry is included in physics because chemical systems would seem to constitute a special class of physical systems. But this impression is mistaken, for what is physical about chemical systems is its components rather than the system itself, which possesses emergent (though explainable) properties in addition to physical properties. (Bunge 1982)

Bunge cites as an example of such an emergent property that of having a composition that changes lawfully in the course of time. The atomic and molecular components do not show this property of composition. Likewise, Primas says that even though we can calculate certain molecular properties, we cannot point to something in the mathematical expressions which can be identified with bonding. The concept of chemical bonding seems to be lost in the process of reduction (Primas 1983). Furthermore, Scerri and McIntyre (1997) argue that such conceptual reduction is not possible in principle due to the very nature of the concepts themselves. The atomic and molecular components do not show the property of composition. Erduran (2007) illustrated the relevance of reduction in chemical education in the context of chemical composition, molecular structure and bonding, all concepts that are promoted as learning outcomes in secondary and tertiary education. She drew from investigations into the reduction theme in the context of water (e.g. Kripke 1971; Putnam 1975) pointing to the following relationship: ‘Water is H_2O’. Water has been a popular topic of discussion among philosophers (e.g. Farrell 1983). Barbara Abbott, for example, dedicated a paper on the observation made by Chomsky (1995) that tea and Sprite are not called water although they contain roughly the same proportion of H_2O as tap water (Abbott 1997). It is common in these discussions to identify the antireduction theme that the concept or the laws of water cannot be reduced to the concept or laws governing H_2O. In a micro-reductive picture, water really is H_2O. H_2O is the essence of the substance which, at the manifested level, is called water. Barnet (2000) argues, however, that even if water is granted to be necessarily composed of H_2O, we should not accept that such rigid designators as ‘H_2O’ and ‘water’ refer to the same thing (Chang 2012).

10.2.2 Supervenience

Supervenience has drawn quite a lot of attention in philosophy of chemistry (e.g. Luisi 2002; Newman 2013). The most common definition of supervenience is that supervenience is a relationship of asymmetric dependence. Two macroscopic systems which have been constructed from identical microscopic components are assumed to show identical macroscopic properties, whereas the observation of identical macroscopic properties in any two systems need not necessarily imply identity at the microscopic level. Some authors have even drawn on the relationship between chemistry and physics to illustrate their basic arguments about the supervenience relationship (Papineau 1993). As an example to contextualise supervenience, Scerri and McIntyre (1997) consider the property of smell. If two chemical compounds were synthesised out of elementary particles in an identical manner, they would share the same smell. Similarly the supervenience argument would entail that if two compounds share the same macroscopic property of smell, we could not necessarily infer that the microscopic components from which the compounds are formed would be identical. Such scenarios can be explored by biochemists and neurophysiologists but whatever the outcome, the question of supervenience of chemistry on physics will depend on empirical facts and not on philosophical considerations.

The case of supervenience highlights the role of empirical chemical research in establishing at least some aspects of the relation between microscopic and macroscopic systems. One educational implication is the importance of emphasising the significant role of empirical research in chemical inquiry (Erduran and Scerri 2003). As an example educational scenario, the question of supervenience can be raised at secondary education through case studies investigating the relationships between the colour, smell and texture and microscopic properties such as molecular structure and bonding. School chemistry is full of concepts that necessarily raise supervenience as an item for discussion. The problem with school chemistry is that the coverage of the relationships at different levels of organisations (i.e. macroscopic and microscopic properties) is often restricted to the coverage of declarative knowledge rather than a sound meta-level interrogation (Erduran et al. 2007).

10.2.3 Explanations

There is now a growing body of work in philosophy of chemistry that highlights aspects of chemical knowledge such as explanations, models and laws. A brief survey will illustrate some of the debates around chemical knowledge. Extended discussions are available elsewhere. For instance, refer to the discussion on chemical explanations and laws in Dagher and Erduran in this handbook. Here we will review some example work to illustrate the nature of debates on the structure of chemical knowledge from a philosophical perspective.

An important form of explanation that pervades all areas of chemistry is lies in electron shells or orbitals. The formation of bonds, acid–base behaviour, redox chemistry, photochemistry and reactivity studies are all regularly discussed by reference to the interchange of electrons between various kinds of orbitals (Scerri and McIntyre 1997). The analysis of explanations in general and physical chemistry may at first sight seem to speak in favour of the epistemological reduction of chemistry to physics, since the discourse of electron shells is thought to belong primarily to the level of atomic physics. However, a more critical examination of the issues involved reveals no such underpinning from fundamental physics. Electronic orbitals cannot be observed according to quantum mechanics, although they remain as a very useful explanatory device. This result is embodied in the more fundamental version of the Pauli exclusion principle, which is frequently forgotten at the expense of the restricted and strictly invalid version of the principle, which does uphold the notion of electronic orbitals (Scerri 1991, 1995). This situation implies that most explanations given in chemistry which rely on the existence of electrons in particular orbitals are in fact 'level-specific' explanations, which cannot be reduced to or underwritten by quantum mechanics. Thus, the explanation of what it is that we seek to know when we engage in chemical explanation would seem to support the explanatory autonomy of chemistry (Scerri 2000). An important implication for chemistry education at higher levels is that the teaching context needs to manifest the useful explanatory nature of electronic orbitals in chemical explanations in a manner consistent with their antirealistic use in quantum mechanics. In other words, there is a distinction to be made about the explanatory status of electronic orbitals in chemistry and their ontological status in quantum mechanics. Reflective classroom discussions based on such distinctions are likely to promote deeper understanding of chemical explanations among university students.

When we turn to organic chemistry, Goodwin (2008) explains that in organic chemistry, phenomena are explained by using diagrams instead of mathematical equations and laws. In this respect, organic chemistry is quite different from the way that explanations are constructed in physical sciences. Goodwin investigates both the nature of diagrams employed in organic chemistry and how these diagrams are used in the explanations of the discipline. The diagrams particularly mentioned are structural formulas and potential energy diagrams. Structural formulas are two-dimensional arrangements of a fixed alphabet of signs. This alphabet includes letters, dots and lines of various sorts. Letters are used as atomic symbols; dots are used as individual electrons, and lines are used as signs for chemical bonds. Structural formulas in organic chemistry are mainly used as descriptive names for the chemical kinds. Thus, structural formula has a descriptive content consisting of a specification of composition, connectivity and some aspects of three-dimensional arrangement. Structural formulas are also used as models in organic chemistry. For example, a ball and stick model is used in the explanations of organic chemistry.

Following a characterisation of some features of structural formulas, Goodwin presents a model of the explanations in organic chemistry and describes how both structural formulas and potential energy diagrams contribute to these explanations. He gives the examples of 'strain' and 'hyper-conjugation' to support his idea about the role of diagrams in organic chemistry as structural explanations. In other words, the structural representations embed assumptions about molecules and how atoms are positioned in relation to one another in molecules. Although schooling introduces students to structural representations, they are often implicit and are not articulated in a way to foster meta-level understanding.

10.2.4 Laws

A great deal of interest has emerged in the study of laws in chemistry (e.g. Christie 1994; Tobin 2013; Vihalemm 2003). Some philosophers of chemistry (e.g. Christie and Christie 2000) as well as chemical educators (e.g. Erduran 2007) have argued that there are particular aspects of laws in chemistry that differentiate them from laws in other branches of science with implications for teaching and learning in the science classroom. A topic of particular centrality and relevance for chemical education is the notion of 'periodic law' which is typically uncharacterised as such:

> Too often, at least in the English speaking countries, Mendeleev's work is presented in terms of the Periodic Table, and little or no mention is made of the periodic law. This leads too easily to the view (a false view, we would submit), that the Periodic Table is a sort of taxonomic scheme: a scheme that was very useful for nineteenth century chemists, but had no theoretical grounding until quantum mechanics, and notions of electronic structure came along. (Christie and Christie 2003, p. 170)

A 'law' is typically defined as 'a regularity that holds throughout the universe at all places and at all times' (Salmon et al. 1992). Some laws in chemistry like Avogadro's law (i.e. equal volumes of gases under identical temperature and pressure conditions will contain equal numbers of particles) are quantitative in nature while others are not. For example, laws of stoichiometry are quantitative in nature and count as laws in a strong sense. Others rely more on approximations and are difficult to specify in an algebraic fashion. Scerri and McIntyre (1997) state that the periodic law seems not to be exact in the same sense as are laws of physics, for instance, Newton's laws of motion. The periodic law states that there exists a periodicity in the properties of the elements governed by certain intervals within their sequence arranged according to their atomic numbers. The crucial feature which distinguishes this form of 'law' from those found in physics is that chemical periodicity is approximate. For example, the elements sodium and potassium represent a repetition of the element lithium, which lies at the head of group I of the periodic table, but these three elements are not identical. Indeed, a vast amount of chemical knowledge is gathered by studying patterns of variation that occur within vertical columns or groups in the periodic table. Predictions which are made from the so-called periodic law do not follow deductively from a theory in the same way in which idealised predictions flow almost inevitably from physical laws, together with the assumption of certain initial conditions.

Scerri further contrasts the nature of laws in physics such as Newton's laws of motion. Even though both the periodic law and Newton's laws of motion have had success in terms of their predictive power, the periodic law is not axiomatised in mathematical terms in the way that Newton's laws are. Part of the difference has to do with what concerns chemists versus physicists. Chemists are interested in documenting some of the trends in the chemical properties of elements in the periodic system that cannot be predicted even from accounts that are available through contributions of quantum mechanics to chemistry. Christie and Christie (2000), on the other hand, argue that the laws of chemistry are fundamentally different from the laws of physics because they describe fundamentally different kinds of physical systems. For instance, Newton's laws described above are strict statements about the world, which are universally true. However, the periodic law consists of many exceptions in terms of the regularities demonstrated in the properties and behaviours of elements. Yet, for the chemist there is a certain idealisation about how, for the most part, elements will behave under particular conditions. In contrast to Scerri (2000), Christie and Christie (2000), and Vihalemm (2003) argue that all laws need to be treated homogeneously because all laws are idealisations regardless of whether or not they can be axiomatised. Van Brakel further questions the assumptions about the criteria for establishing 'laws'. An implication for chemical education is that such discussions on the philosophical characterisation of laws would extend the periodic table as a taxonomic device and promote understanding of its character as a way of reasoning in chemistry (Erduran 2007).

10.2.5 Models

The *Stanford Dictionary of Philosophy* illustrates the role of models and modelling in chemistry as follows:

> Almost all contemporary chemical theorizing involves modeling, the indirect description and analysis of real chemical phenomena by way of models. From the 19th century onwards, chemistry was commonly taught and studied with physical models of molecular structure. Beginning in the 20th century, mathematical models based on classical and quantum mechanics were successfully applied to chemical systems.

The role of models in chemistry has been underestimated since the formulation of quantum theory at the turn of the century. There has been a move away from qualitative or descriptive chemistry (which relies on development and revision of chemical models) towards quantum chemistry (which is based on the quantum mechanical theory). Increasingly, chemistry has emerged as a reduced science where chemical models can be explained away by physical theories:

> In the future, we expect to find an increasing number of situations in which theory will be preferred source of information for aspects of complex chemical systems. (Wasserman and Schaefer 1986, p. 829)

The presence of models in different disciplines such as cognitive psychology, philosophy of science, chemistry or education makes it even more difficult to come up with a single definition for the term ‘model’ for educational purposes. For example, in a review of the literature on the interdisciplinary characterisations of models, Erduran and Duschl (2004) discussed three different definitions of models in chemistry. The term model can refer to a material object, such as a construction. For example, a chemist can construct a model to represent the structure of a molecule so as to explain the motions of the atoms in the molecule. Another definition involves the model as a description, an entity that is merely imagined and described rather than to one is perceivable. Finally a model can be defined to involve a system of mathematical equations so as to give exactness to the description such as developing a model considering the wave equation for a hydrogen atom.

Atomic and molecular orbitals, formulated through quantum chemistry, have been used to explain chemical structure, bonding and reactivity (Bhushan and Rosenfeld 1995; Nagel 1961). Woody (1995) identified four properties of models: approximate, projectability, compositionality and visual representation. A model’s structure is *approximate.* In other words, the model is an approximation of a complete theoretical representation for a phenomenon. The model omits many details based on judgments and criteria driving its construction. Another characteristic of a model proposed by Woody is that a model is *productive* or *protectable.* In other words, a model does not come with well-defined or fixed boundaries. While the domain of application of the model may be defined concretely in the sense that we know which entities and relationships can be represented, the model does not similarly hold specifications of what might be explained as a result of its application. Woody further argues that the structure of the model explicitly includes some aspects of *compositionality.* There is a recursive algorithm for the proper application of the model. Thus, while the open boundaries of the model allow its potential application to new, more complex cases, its compositional structure actually provides some instruction for how a more complex case can be treated as a function of simpler cases. Finally, in Woody’s (1995) framework, a model provides some means of *visual representation.* This characteristic facilitates the recognition of various structural components of a given theory. Many qualitative relations of a theoretical structure can be efficiently communicated in this manner. Although chemical education research literature contains a vast number of studies on models and modelling (e.g. Carr 1984; Coll and Taylor 2005; Gilbert 2004;

Justi and Gilbert 2003; Justi 2000), only a few studies have taken on epistemological perspective on the nature of models (e.g. Adúriz-Bravo 2013; Chamizo 2013; Erduran 2001).

10.2.6 Chemistry as Language

Arguments have been put forth to characterise chemistry as a language. For example, Lazslo (2013) argues that the analogy of language 'forces us to reconsider the usual positioning of chemistry, in classification of the sciences, between physics and biology. It reclaims chemistry as a combinatorial art'(p. 1701). Jacob (2001) defines chemistry as an experimental science that transforms both substances and language. On the one hand, chemists analyse and synthesise new compounds in the laboratory; on the other, they make analytical and synthetic statements about these compounds in research articles. Therefore, Jacob emphasises the necessity of understanding chemists' use of their language, what rules govern the use of chemical language and what consequences the utilisation of this language have for chemistry as a whole. It is essential to distinguish not only between chemical experiments and chemical language but also between different levels of chemical language. Jacob classifies the levels of chemical language as chemical symbols for substances, vocabulary (ideators and abstractors) that enables chemists to talk about substances in general, terms (theories and laws) that are used to discuss abstractors and language of philosophy (theories, their origin and their empirical basis). All levels of chemical language are vital for chemical research.

In particular, the relationship between the chemical symbols used to represent substances and the substances themselves is most central for the research chemist. Jacob defines chemical symbolism as a language and investigates the empirical basis of chemical symbolism. He also outlines the interdependence between the different operations of analysis and synthesis on the bench and on the blackboard. Furthermore, he discusses the influence language has on the progress of chemical research in general and the potential limitations the use of a specific chemical language poses for research in particular.

An aspect of Jacob's work on chemical language concerns chemical symbolism. Jacob explains some aspects of chemical symbolism. Chemical symbolism consists of an alphabet, a particular syntax and a set of semantic rules. Chemical alphabet consists of approximately 110 symbols representing the known chemical elements (e.g. Na, Cl). Elemental symbols can be combined in order to form a chemical formula (e.g. NaCl) and reaction equations (e.g. $2Na + Cl_2 \rightarrow 2NaCl$). These combinations of symbols follow a set of formal rules which are defined as chemical syntax. Chemical syntax covers empirical rules regarding valency, oxidation state, electronegativity, affinity and reaction mechanisms (Psarros 1998, as cited in Jacob 2001).

Chemical orthography provides the rules for combination of elements in formulas (e.g. Na and Cl can be combined to NaCl using the rule that 1 Na can be combined with 1 Cl). Chemical grammar provides the rules for reaction equations (e.g. stoichiometric coefficients, use of unidirectional or equilibrium arrows, reactions conditions). The grammar rules of the reaction formula $2Na + Cl_2 \rightarrow 2NaCl$ are determined by the orthography of Na, Cl_2 and NaCl. Chemical semantics discusses the meaning of symbols, formulas and reactions (e.g. NaCl as lump of salt). While chemical semantics describes the relationship between existing substances and their linguistic representations, chemical syntax enables chemists to form new symbols as representations of substances not yet synthesised. The meaning of NaCl (chemical, physical, social, cultural) is independent from both orthographic (e.g. NaCl vs. Na_3Cl) and grammatical correctness (e.g. $2Na + Cl_2 \rightarrow NaCl_2$). The distinction between syntactic and semantic rules allows for an important asymmetry between operations with language and operations with compounds. According to Jacob (2001) the asymmetry between syntactic and semantic rules is the basis of planning new reactions. The distinction between syntactic and semantic properties of chemical symbolism allows introduction of chemical formulas that are syntactically correct but do not (yet) have an empirical basis. The relevance of chemical language for chemistry education has been illustrated in the context of textbooks (e.g. Kaya and Erduran 2013).

10.2.7 Ethics in Chemistry

The final example aspect of philosophy of chemistry concerns ethics of chemistry. Recent landscape in science education at both the policy (e.g. National Research Council 1996) and research (e.g. Zeidler 2003) levels promotes the education of individuals to be able to make informed decisions and justified moral choices on scientific issues ranging from genetically modified foods to environmental protection (Kovac 2004). Erduran (2009) highlighted Kovac's work as a key area of contribution from philosophy of chemistry to chemical education as ethics raises relevant questions such as 'What aspects of chemical knowledge relate to ethical concerns? What are the moral implications of chemical knowledge?' Kovac highlights the particular ways in which chemists' lives are defined by problems of ethics:

> Ordinarily chemists are not independent practitioners like lawyers and doctors, but instead work within institutions such as colleges and universities, government agencies and industrial concerns. As a result, they often have several roles. For example, I am both a chemist and a professor and each profession has its own history and culture. In industry a chemist is certainly an employee and might also be a manager. All industrial chemists must balance their ethical obligations to chemistry as a profession with their contractual and ethical obligations to their employers. In addition, all chemists are also citizens and human beings with the civic and moral responsibilities that accompany those roles. One of the goals of a philosophy of the profession should be to clarify the ethical responsibilities of chemists as chemists, as opposed to their responsibilities in other roles. Conflicts can occur. (Kovac 2000, p. 217)

Chemists work in a variety of contexts and consequently are confronted with a broad array of ethical problems. The chemical industry is interlinked with societal questions and demands and therefore gives rise to complex issues concerning the relationship of science and society. Kovac (2000) explores the relationship between professionalism and ethics. Since writing *The Ethical Chemist*, a collection of cases and commentaries for the teaching of scientific ethics to chemists, Kovac has been investigating ethics as an integral part of chemistry. In particular, he explores those aspects of chemical ethics that go beyond the demands of ordinary morality, the requirements of law and the pressures of the market. Furthermore, Kovac suggests that a healthy dialogue concerning professionalism and ethics is essential to a broader philosophy of chemistry. While a discussion of concepts is the core of a philosophy of science, science is, after all, public knowledge developed by a community. What is unique about chemistry as a science is partly a result of the uniqueness of the chemical community and its history. Studying chemistry as a profession will help reveal the essence of chemistry as a science.

While there has been much recent interest in the ethics of science, most of the literature is rather broadly conceived, treating science as a single enterprise (Kovac 2000). According to Kovac, here is little, if any, recognition that each scientific discipline has its own perspective on professionalism and ethics. For example, David B. Resnick's book, *The Ethics of Science: An Introduction* (Resnik 1998), for all its strengths, never discusses the differences between the various sciences. There is a substantial literature of casebooks designed to provide materials for courses in scientific ethics. Some of these, such as *Research Ethics: Cases & Materials*, edited by Robin Levin Penslar (1995), provide a broader philosophical introduction and cases in a number of disciplines, while others, such as Kovac's work (Kovac 2004), focus on practical ethics in a single discipline. The literature on ethics in chemistry is scarce indeed. However, even the existing debates provide some potential useful guidelines for chemical education research and practice. For instance, these perspectives raise questions for educational research: 'What is the nature of moral reasoning in chemistry and how could such moral reasoning be incorporated in learning?'

10.3 Debates on Constructivism and Nature of Science (NOS) Research

The preceding brief survey of perspectives from philosophy of chemistry for applications in chemical education research and practice illustrates so far some of the specific themes that are relevant for import in chemical education. There is further scope for the treatment of philosophical perspectives in chemical education particularly in two broad areas that have preoccupied educators: constructivism (e.g. Taber 2006) and nature of science (NOS) (e.g. Lederman et al. 2002; McComas 1998). The treatment of philosophical perspectives in chemical education research has conventionally focussed on themes such as relativism, objectivism and realism (e.g. Herron 1996). Eric Scerri has maintained the thesis that such philosophical concepts have been misinterpreted in the work of some chemical educators, and at times, they are at odds with scientific ideas:

> I think that if one looks closely at the basic philosophical positions offered by some chemical constructivists, one sees many radical themes that are not only open to serious questioning but can also be construed as being anti-scientific. (Scerri 2003, p. 468)

Scerri further argues that one remedy to this philosophical confusion is more use of philosophy of chemistry in chemical education research. Scerri reflects on the status of chemical education research by highlighting how for some chemists 'research in chemical education represents a soft-option best suited for those who are not capable of succeeding in 'real chemistry' research' (p. 468). He continues to argue that some of the blame in the low reputation of chemical education research among chemists can be attributed to the philosophical confusions demonstrated by chemical educators. In a response to this criticism, Erduran (2009) acknowledges that such confusions do exist but considers chemical education research beyond university chemistry departments to illustrate the diversity of the chemical education community. She highlights the extensive body of research in chemical education (e.g. Gable and Bunce 1984) and argues that the perception of chemical education research as a soft option to doing hard science of chemistry is reflective of lack of knowledge that there is a formalised discipline called 'science education' with its own body of journals, conferences, societies as well as funding agencies. Furthermore, Erduran (2009) notes that it is also important to note that 'school chemistry' is not the same as 'chemistry'. The goals and aims of education do not necessarily correspond to goals and aims of chemical research be they in the form of hard science or as an object of investigation by philosophers or historians. For instance, the historical progression of ideas in science may not be followed in the same order in the classroom for pedagogical purposes, yielding a vision of science devoid of historical context. However at times, sequences of concepts introduced in the classroom may serve learners' understanding if they do not come in the historical order. Indeed often science education discards many old theories and models in favour of recent accounts so as not to confuse students or impart potential misconceptions that have been dealt with throughout history by scientists. Overall, such approaches demarcate the purposes and processes of school versus institutional science. Furthermore, school science as advocated in important policy documents worldwide (e.g. NRC 1996) is one that recognises the right for everyone to be scientifically literate, not just those who will become scientists.

Constructivism has been a major theme within the science education community. Indeed, the vast body of empirical work that emerged on learners' ideas in science was stimulated by the constructivist movement (e.g. Driver et al. 1996). As a result, a significant amount of literature is now available on how learners of different age groups understand key chemical concepts (e.g. Duit 2012). As Yeanny pointed, constructivism has been a unifying theme for 'thinking, research, curriculum development, and teacher education' (Yeany 1991, p. 1), and he added that 'there is a lack of polarised debate'. However, despite this significant research effort, there have been serious criticisms of this area of work (e.g. Irzik 2000; Matthews 1994, 1998; Mugaloglu 2001). In S*cience Teaching: The Role of History and Philosophy of Science* (1994/2014), Matthews made a critical analysis of the philosophical foundations of constructivism and its implications for science education. Although there are different versions of constructivism, most of them define knowledge as an intellectual and social construction without reference to 'justified true belief (JTB)' theory (Mugaloglu 2001).

The debate on constructivism is essentially an epistemological war between those who take a realist position and those who take a relativist or constructivist position in relation to scientific knowledge and the learning of science (Scerri 2003, p. 3). Scerri (2003) refers to Gross and Levitt's book *Higher Superstition* (1998) when arguing that some studies on the nature of science are 'seriously mistaken and are having a damaging influence upon scholarly work, the public image of science, and last but not least, on science education' (p. 359). Although the war is going on mainly in the philosophy of science arena, most chemists explicitly or implicitly take one or the other of these two positions when thinking about chemistry and their knowledge about chemistry.

Taber (2006) reviews such criticisms in terms of constructivism's philosophical underpinning, the validity of its most popular constructs, the limited scope of its focus, and its practical value to science teaching. Furthermore he frames constructivism as an area of work as a Lakatosian research programme (RP) and explores the major criticisms of constructivism from that perspective. He argues that much of the criticism may be considered as part of the legitimate academic debate expected within any active RP, i.e. arguments about the auxiliary theory making up the 'protective belt' of the programme. It is suggested that a shifting focus from constructivism to 'contingency in learning' will allow the RP to draw upon a more diverse range of perspectives, each consistent with the existing hard core of the programme, which will provide potentially fruitful directions for future work and ensure the continuity of a progressive RP into learning science.

Chemistry educators have good reasons to follow the debates on constructivism. First, to develop an understanding of how chemistry is conceptualised and how chemistry is learned, the debate about its nature, epistemology and ontology is crucial to acknowledge. Investigating the nature of chemistry can only lead to more effective teaching of chemistry. This explains why 'nature of science' is one of the most studied topics in the literature of science education (Chang et al. 2010). Second, the literature includes evidence to suppose a relationship between the epistemological positions of teachers and the learning paradigms that influence their teaching. In other words, while chemistry teachers are teaching chemistry, they implicitly or explicitly but necessarily present a philosophical position about chemistry (Chamizo 2007; Erduran and Scerri 2003).

One of the central and broad areas of research in science education that has harboured the debates on constructivism including its epistemological and ontological foundations is called nature of science (NOS). The predominant definition of the NOS in the empirical studies on teachers' and students' perceptions of science has relied on the characterisation of science primarily relative to the cognitive, epistemic and social aspects of science and has been limited in terms of their conceptualisations of science from broader perspectives on science (e.g. Allchin 2011). The collective set of learning goals for understanding the NOS is summarised in the 'consensus' view of NOS (Lederman et al. 2002; McComas 1998) which has the following tenets:

(a) Tentativeness of Scientific Knowledge: Scientific knowledge is both tentative and durable.
(b) Observations and Inferences: Science is based on both observations and inferences. Both observations and inferences are guided by scientists' prior knowledge and perspectives of current science.

(c) Subjectivity and Objectivity in Science: Science aims to be objective and precise, but subjectivity in science is unavoidable.
(d) Creativity and Rationality in Science: Scientific knowledge is created from human imaginations and logical reasoning. This creation is based on observations and inferences of the natural world.
(e) Social and Cultural Embeddedness in Science: Science is part of social and cultural traditions. As a human endeavour, science is influenced by the society and culture in which it is practiced.
(f) Scientific Theories and Laws: Both scientific laws and theories are subject to change. Scientific laws describe generalized relationships, observed or perceived, of natural phenomena under certain conditions.
(g) Scientific Methods: There is no single universal step-by-step scientific method that all scientists follow. Scientists investigate research questions with prior knowledge, perseverance and creativity.

In this propositional characterisation of NOS, science is presented in an epistemologically and ontologically flat and undifferentiated landscape, broad and lacking sufficient detail to indicate the nuances that characterise branches of science. For instance, with respect to (f), there is no consideration of how laws might have different characteristics in different sciences. As illustrated earlier in the work of Christie and Christie (2000) and also argued by Erduran (2007) in the context of chemical education, 'laws' can have very different meanings in chemistry versus physics. Furthermore, question the very characterisation of 'science' in NOS by asking 'the nature of which science NOS characterisations capture in the first place'. The particular instances of reduction, supervenience as well as the nature of models, laws and explanations and chemistry as language all point to ample evidence from philosophy of chemistry that the contemporary characterisations of NOS are underspecified.

In summary, perspectives from philosophy of chemistry can provide a new and fresh lens by which to view and interpret constructivism and NOS with respect to science education. These perspectives help clarify the ontological and epistemological status of chemistry in ways that traditionally philosophy of science has not sufficiently captured. In turn, the insight into the nature of chemistry can help inform the goals and content of chemical education.

10.4 Applications of Philosophy of Chemistry in Chemical Education

The applications of philosophy of chemistry in chemical education theory and practice have been minimal (Erduran 2013, 2000a, b). A rare volume on the subject was compiled in the journal *Science & Education*. The volume consists of papers that deal with a range of issues raised in philosophy of chemistry in application to chemical education. One set of papers focus on the nature of chemical knowledge, particularly in relation to models, explanations and laws. Woody (2013) uses the ideal gas law as an example in reviewing contemporary research in philosophy of science concerning scientific explanation. She clarifies the inferential, causal, unification and erotetic conceptions of explanation. Tobin (2013) provides an overview of the laws in chemistry and reflects on the recent debates on the particular and universal nature of laws, concluding that while generalisations in chemistry are diverse and heterogeneous, a distinction between idealisations and approximations can nevertheless be used to successfully taxonomise them. Adúriz-Bravo (2013) challenges the received, syntactic conception of scientific theories and argues for a model-based account of the nature of science. The significance of models and modelling in chemistry is further highlighted through a typology of models and their relation to modelling (Chamizo 2013). Izquierdo-Aymerich (2013) argues for the generation of chemical criteria from the history and philosophy of chemistry for informing the design of chemistry curriculum.

The special issue volume consists of a second set of papers that focus on particular epistemological themes. The authors extend these debates to the curricular, textbook and teaching contexts and, in so doing, elaborate on their potential instantiation in education. Newman (2013) provides a model for teaching chemistry with the potential to enhance fundamental understanding of chemistry. Lazslo (2013) argues that chemistry ought to be taught in like manner to a language, on the dual evidence of the existence of an iconic chemical language, of formulas and equations and of chemical science being language-like and a combinatorial art. Universality and specificity of chemistry are interrogated by Mariam Thalos who argues that chemistry possesses a distinctive theoretical lens—a distinctive set of theoretical concerns regarding the dynamics and transformations of a variety of organic and nonorganic substances (Thalos 2013). While she agrees that chemical facts bear a reductive relationship to physical facts, she argues that theoretical lenses of physics and chemistry are distinct. Manuel Fernandez-Gonzalez discusses the concept of pure substance, an idealised entity whose empirical correlate is the laboratory product (Fernandez-Gonzalez 2013). A common structure for knowledge construction is proposed for both physics and chemistry with particular emphasis on the relations between two of the levels: the ideal level and the quasi-ideal level. Kaya and Erduran focus on concept duality, chemical language and structural explanations, to illustrate how chemistry textbooks could be improved with insights from such work (Kaya and Erduran 2013). They provide some example scenarios of how these ideas could be implemented at the level of the chemistry classroom. Talanquer presents a case that dominant universal characterisations of the nature of science fail to capture the essence of the particular disciplines. The central goal of this position paper is to encourage reflection about the extent to which dominant views about quality science education based on universal views of scientific practices may constrain school chemistry (Talanquer 2013).

Activities, practices and values of chemistry are interrogated in a third set of papers. Earley recommends that chemistry educators shift to a different ‘idea of nature’, an alternative ‘worldview’ (Earley 2013). Garritz (2013) illustrates how teaching history and philosophy of physical sciences can illustrate that controversies and rivalries among scientists play a key role in the progress of science and why scientific development is not only founded on the accumulation of experimental data. The case of quantum mechanics and quantum chemistry is used as an example because it is historically full of controversies. Ribeiro and Pereira (2013) illustrate how pluralism in philosophical perspectives can result in different cognitive, learning and teaching styles in chemical education. Their paper reports on the authors' experiences in Portugal in drafting structural ideas and planning for the subject 'didactic of chemistry' based on the philosophy of chemistry. Vesterinen et al. (2013) assess how the different aspects of nature of science (NOS) were represented in Finnish and Swedish upper secondary school chemistry textbooks. They present an empirical study where dimensions of NOS were analysed from five popular chemistry textbook series. Vilches and Gil-Perez (2013) reflect on the UN Decade of Education for Sustainable Development and how chemical education for sustainability remains practically absent nowadays in many high school and university chemistry curricula all over the world. They explore the belief that genuine scientific activity lies beyond the reach of moral judgment logically. They propose possible contributions of chemistry and chemical education to the construction of a sustainable future. Sjostrom (2013) is concerned with Bildung-oriented chemistry education, based on a reflective and critical discourse of chemistry. This orientation is contrasted with the dominant type of chemistry education, based on the mainstream discourse of chemistry. Bildung-oriented chemistry education includes not only content knowledge in chemistry but also knowledge about chemistry, both about the nature of chemistry and about its role in society.

In summary, there is now an emerging body of scholars including philosophers, educators and chemists who are working on the intersections of philosophy of chemistry and chemical education. The review so far illustrates the diversity of this work that warrants the pursuit of future work to contribute further to scholarship in this area. So far the discussion has been at a conceptual level and provided a rationale for the relevance of philosophical issues in chemistry and chemical education. In the next sections, the focus will be on practical instantiations and highlight some concrete instances in educational contexts for the inclusion of philosophical perspectives on chemistry. These will include implications and applications in learning, teaching, teacher education and textbooks.

10.4.1 Learning

Learning of chemistry has conventionally been framed in terms of problem solving (e.g. Gable and Bunce 1984; Lythcott 1990), concept learning (e.g. Cros et al. 1987; Nussbaum and Novak 1979) and learning of science-process skills (e.g. Heeren 1990; Yarroch 1985). The inclusion of philosophical perspectives in chemistry learning challenges such traditional characterisations of learning. Learning of the nature of chemical knowledge defined in terms of conceptual understanding does not acknowledge the learning of criteria and standards that enable knowledge generation, evaluation and revision in chemistry. For instance, there is little understanding of the patterns in students' ideas of how chemical laws are generated and refined. It is possible to question the extent to which research on students' and teachers' epistemologies of science has captured sufficiently the intricacies of disciplinary nuances such as those illustrated by philosophy of chemistry. How do learners, for instance, engage in discussions on reduction? What are their views on the ontological dependence of chemistry and physics? What are the trajectories of learning and the developmental patterns in understanding the supervenience issue?

Concentrating on learning trajectories is particularly relevant when evidence from higher education is exemplified. Students in advanced chemistry classes demonstrate having difficulties with many aspects of chemistry. For instance, in a study conducted by Cros and his colleagues (1987), 95 % of a large sample of university students had difficulty interpreting the Bohr model of the atom. University students also experience much difficulty with acid–base chemistry especially with Lewis model which combines acidity and basicity concepts with electrophilicity and nucleophilicity (Zoller 1990). These examples call for a further examination of how chemical explanations are introduced in the classroom. Deeper philosophical reflections on the nature of chemical explanations and how they are generated and evaluated are likely to improve students' understanding of key concepts in chemistry. In October, 1999, an elective course on the philosophy of chemistry was opened to undergraduates at the University of Exeter. Jones and Jacob (2003) published a brief report about the course, including its benefits and drawbacks. They emphasised that teaching such a course entailed departures from traditional chemistry teaching and consequent challenges. Since philosophy of chemistry was a new field, it was difficult even to find a textbook. Journals such as *HYLE* were the main source for the course at that time.

10.4.2 Teaching

Perspectives from philosophy of chemistry present the potential of motivating debates for the chemistry classroom. Building on Stroll's (1991) work, Erduran (2005) provided a particular task to illustrate how teaching could proceed in the context of a philosophical discussion. The example of 'water' presents opportunities to raise themes such as reduction and supervenience at the level of the classroom. There is the relation between the physical properties of 'water' (e.g. water boils at 100 C) and the structural features of 'H_2O' (e.g. the bond angle of 104.5 C). How, if at all, do these properties relate to each other? Can the macroscopic properties be reduced to microscopic properties? Are there any circumstances under which water is not H_2O? In this case substances with equivalent concentrations of H_2O concentration are nevertheless regarded as different and not 'water'.

As an introduction, students can be confronted with their basic assumptions about water. They can be presented with a glass full of water, with the written formula H_2O and the written word 'water'. Questions that target chemical composition, molecular structure and bonding can be presented in a way that would elicit the theme of reduction. For instance,

Does H_2O have the same chemical composition as water?
Could a single water molecule boil at 100 C?
Is H_2O the same thing as water?

could be useful for secondary schooling and can be revisited at higher levels of education where more in-depth considerations could occur. An introduction to such questions would hopefully challenge students' assumptions about seemingly straightforward relationships between macroscopic properties and representation of microscopic realty of molecules. Here, the intention is not to get students to answer these questions but to arouse their curiosity about one of the fundamental ways of thinking in chemistry: the interplay of the microscopic, symbolic and macroscopic levels. Furthermore, creating a context where explicit comparisons between symbolic, abstract and concrete experiences of substances are made is likely to immerse students in a philosophical mindset. The presentation of the following set of statements is likely to raise further debate at the level of the classroom due to the logical absurdity that it embodies:

Water = H_2O
Ice = H_2O
Therefore, water = ice

In this framework, the students would identify the logic of the above equations and face an absurd conclusion. The absurdity of the conclusion, then, provides the motivation for discussion and raises issues about what counts as water and ice beyond a microscopic definition of H_2O. In other words, questions such as 'can the experience of water and ice as colourless liquid and white solid be reduced to H_2O?' could stimulate the conversation. The process of reasoning from the premises to the conclusions would necessitate the generation of counter-arguments to justify why the conclusion cannot be true.

Van Brakel (2000) argues that the 'water = H_2O' equation is not true because of the problem of isotopes and the fact that water is not 100 % H_2O. De Sousa (1984) furthermore argued that H_2O 'is a chemical characterization of water, not a physical one. Physically it turns out that water is a mixture of several sorts of molecules: ones containing Oxygen-16 and one containing the isotope Oxygen 18, as well as ones containing isotopes of hydrogen (deuterium or tritium)' (p. 571). Hence, H_2O is the *chemical* essence of water, not *the* essence of water. Here we see the potential for introducing, at upper secondary schooling, other concepts such as isotopes and concentration to supplement the discussion.

The role of the teacher in this scenario would be more of a facilitator of discussion. Different points of view with respect to such questions can be recorded publicly in the classroom so that students are provided with alternative explanations. For instance, as an extreme case, a sceptic student might argue that the water in the glass really has nothing to do with the formula H_2O and that these conventions are fictions of chemists' imaginations. Alternatively, another student might defend the position that even if he/she believes that the water in glass has something to do with the formula H_2O, he/she only knows so because the textbook said so. In either case, students can be encouraged to provide evidence to justify their points of view. Overall, pedagogical strategies of questioning, coordinating discussions, task generation and management would need to be informed by the philosophical accounts of reduction and supervenience.

10.4.3 Teacher Education

According to Erduran and colleagues (2007), aligning teaching and learning with the philosophy of chemistry is a challenge for teachers who have had little exposure to issues of chemical knowledge beyond content knowledge. Schwab (1962) argued that teachers should learn the content of a domain and also the epistemology of the domain. Erduran (2009) stated, 'For chemistry teaching to be effective, prospective teachers will need to be educated about how knowledge is structured in the discipline that they are teaching. Practice and theory of future teacher education, then, will need to be informed by and about philosophy of chemistry.' Erduran and Scerri (2003) state that an understanding of philosophy of chemistry is likely to reinforce teachers' content knowledge such as quantum mechanics, periodicity and structure/function relationships in chemistry.

Apart from an understanding of the content (or subject) domain and the epistemology of the domain, teachers need to have understanding of how to transform these notions into teachable scenarios (Loucks-Horsley et al. 1990). Shulman (1986) has provided a powerful construction 'pedagogical content knowledge (PCK)' to illustrate this kind of understanding and knowledge that teachers need to have. He described PCK as 'The most useful forms of content representation… the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others' (p. 9). For teachers to effectively implement philosophical perspectives in the chemistry classroom, their PCK would need to embrace philosophy of chemistry. There is considerable literature on teacher education and professional development in science education (e.g. Wallace and Louden 2000). Despite addressing the question of teacher education from separate perspectives and disciplines, a common vision of effective professional development exists (Loucks-Horsley et al. 1998, 1990). According to that shared vision, the best professional development experiences for science educators include the following guidelines (Loucks-Horsley et al. 1998):

- They are driven by a clear, well-defined image of effective classroom learning and teaching.
- They provide teachers with opportunities to develop knowledge and skills and broaden their teaching approaches, so they can create better learning opportunities for students.

- They use instructional methods to promote learning for adults which mirror the methods to be used with students.
- They build or strengthen the learning community of science and mathematics teachers.
- They prepare and support teachers to serve in leadership roles if they are inclined to do so. As teachers master the skills of their profession, they need to be encouraged to step beyond their classrooms and play roles in the development of the whole school and beyond.
- They consciously provide links to other parts of the educational system.
- They include continuous assessment.

However, for philosophy of chemistry to be of useful for teacher education, a focus on the content area is vital. A vast amount of research on professional development of science teachers supports this observation (e.g. Zohar 2004). The preceding discussions in this chapter on some representative themes from philosophy of chemistry including reduction, supervenience and the domain-specific characterisations of models, laws and explanations begin to provide some guidelines for what to include as outcomes of teachers' learning.

10.4.4 Textbooks

Textbooks are considered as one of the most important guides for chemistry teachers. However, numerous authors have already questioned the quality of the content of textbooks in terms of their inclusion of historical and philosophical perspectives. For example, Rodriguez and Niaz (2002) questioned *'How criteria based on history and philosophy of science can be used to evaluate presentation of atomic structure in general chemistry textbooks?'* The study revealed that the textbooks 'distort the historical facts'. In addition, the philosophical perspective in the textbooks supports the idea of inductivism (Rodriguez and Niaz 2002, p. 437). Gillespie (1997) argued that change in general chemistry might require reform in chemistry textbooks. Chemistry education researchers critically analysed the chemistry textbooks in terms of their approach, instructional structure, conceptual framework and content analysis. For instance, Kauffman (1989) criticised the chemistry textbooks in terms of the view that they presented. He stated that textbooks 'failed to make the fact clear to students that chemistry is a human enterprise' (p. 82). Moreover, he emphasised teaching the concepts such as scientific progress, focusing on the variety of the scientific method, human values and the importance of process rather than products. To do so, he recommended the inclusion of history of chemistry into the curriculum as a separate course.

There is substantial amount of work on the inclusion of historical case studies in textbooks and the investigation of chemistry from a historical perspective (e.g. Chamizo 2007; Niaz 2008). At the beginning of the twentieth century, William Ostwald emphasised that in the textbooks a philosophical chapter was presented either at the beginning of the book as an introduction or at the end of the book as a summary with a deductive manner (cited in Rodriguez and Niaz 2002, p. 423). Chemistry education researchers should scrutinise the benefits and ways of inclusion of philosophy of chemistry into chemistry textbooks. Just as in the case of historical approach, this inclusion needs to go hand in hand with the curriculum and textbooks reforms so as to provide the teachers with an appropriate content and support in the teaching of chemistry from a new perspective.

A potential area of research for chemical educators is the investigation of existing textbooks for their philosophical content and reference to a set of criteria informed by discussions from philosophy of chemistry. Kaya and Erduran (2013) have done just that by investigating the present textbooks on their inclusion of philosophical perspectives. They have applied Laszlo's (1999) notion of concept duality, Jacob's (2001) descriptions of chemical language and Goodwin's (2008) explication of structural explanations in organic chemistry to highlight the particular ways in which chemical knowledge is structured. Examples of textbooks and curricula were used to illustrate that even though the mentioned aspects of are relevant to educational contexts, the philosophical dimensions of this coverage is absent in textbooks and curricula. The emphasis in the use of these features of chemical knowledge seems to be more on the conceptual definitions rather than on their 'epistemological or ontological nature'. Erduran and Kaya argued that chemical education will be improved through the inclusion of the philosophical perspectives in chemistry teaching and learning by highlighting the specific ways in which chemical reasoning functions. Chemistry educators emphasised that chemistry education theory and practice would benefit from applications of philosophy of chemistry (Adúriz-Bravo and Erduran 2003), especially for teaching and learning the nature of chemical knowledge. For example, the textbooks could present the discussion about nonreferring terms in chemical explanations such as orbitals and electronic explicitly. Then the classification of 'explanatory status of electronic orbitals in chemistry and their ontological status in quantum mechanics' can also be used in educational context to overcome the movement towards an antirealistic understanding of chemistry (Erduran and Scerri 2003).

Moreover, the textbooks should also guide the teachers and students in understanding how chemical knowledge constructed. Evidence in the literature confirms that both chemistry teachers and students have problems in understanding the nature of models and modelling. Erduran et al. (2007) like Gilbert (1997) argue that teachers conceive scientific models in mechanical terms and believe that models are true pictures of non-observable phenomena and ideas. Thus, learning how to make model is usually excluded from the curriculum and textbooks. This is particularly because of the fact that chemistry education has not yet position the importance of models in construction of chemical knowledge as suggested by philosophy of chemistry. Moreover, inclusion of the nature of models and modelling is vital in explaining both the ontological and epistemological relationship between microscopic and macroscopic entities.

10.5 Conclusion

The discussion in this chapter so far illustrates how philosophy of chemistry can contribute to chemical education research and practice. In particular, it raises questions about epistemology, ontology, ethics and linguistics in relation to how chemical education defines, positions and encapsulates the various dimensions of chemistry for the purposes of education. It illustrates how philosophical perspectives on chemistry can contribute to more nuanced versions of NOS in science education. A significant shortcoming of the NOS research in science education has been its lack of differentiation of scientific knowledge with respect to its disciplinary variations. Philosophy of chemistry illustrates not only the epistemological status of chemical knowledge but also its ontological undertones. This is particularly important with respect to the debates on constructivism and relativism.

As a point of warning, Erduran (2013), in her editorial of the special issue of *Science & Education* on the applications of philosophy of chemistry in chemical education, argues that the infusion of philosophical perspectives will need to be mindful of the research evidence on teaching and learning, as well as professional development of teachers. There is substantial evidence that educational reform is difficult to implement at the level of the classroom and much research evidence remains as rhetoric with no impact on practice (e.g. Au 2007; Elmore 2004; Fullan 2007). Effective incorporation of philosophical perspectives in chemical education will require systematic and well-designed research to validate the utility and influence of relevant strategies. For example, in the example about the debate on the composition of water, such a scenario will need to be introduced to teachers in a way that would be mindful to where the existing conceptions of teachers are in the uptake of such views. Professional development of teachers will be required to ensure that teachers themselves are convinced of different ways of teaching chemistry. Investigating the strategies that are effective in imparting learning on students will be essential. In short, empirical testing and validation of approaches will hold the final say in the utility of philosophy of chemistry at the level of the classroom. This is not to say that having argued so far for the inclusion of philosophy of chemistry in chemical education, the authors do not perceive its potential use in practice. To the contrary, it is the commitment and belief in the potential of philosophy of chemistry in improving the quality of teaching and learning of chemistry that has led us to write this chapter in the first place. There is place for caution and mindfulness in the educational and pedagogical manifestations of philosophical ideas in light of evidence from science education research on the difficulties inherent in educational reform.

Finally, empirical data on the implementation of philosophical perspectives in the chemistry classroom is likely to contribute to philosophy of chemistry itself. When the vast amount of literature on children's misconceptions about a wide range of scientific concepts is considered (e.g. Duit 2009), a major observation is that some of children's conceptions are similar to historical forms of thought. It has been argued, thus, that science learning can follow the sort of conceptual change that underlies the scientific process itself. Indeed a plethora of studies have emerged in the misconceptions literature on this very issue in the 1990s. The depth, the insight and the creativity of children's thinking on philosophical accounts of chemistry—for instance, in relation to the evaluation of everyday experiences of substances or the conceptualisation of chemistry as a technoscience (e.g. Ihde 2003)—could potentially raise issues for debate within philosophy of chemistry. It is indeed such empirical instantiation of chemical reasoning from a philosophical perspective in not just students but also teachers that can provide a unique sample for philosophers of chemistry to investigate, thereby engaging with educators in constructive dialogues about the nature of chemistry.

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Chapter 11
The Place of the History of Chemistry in the Teaching and Learning of Chemistry

Kevin C. de Berg

11.1 Introduction

Numerous isolated appeals for the introduction of more history into the undergraduate chemistry curriculum have been made since the 1950s but with limited success. For example, Conant (1951) used the historical case study approach in teaching science to undergraduate students at Harvard, and his case studies included examples from chemistry, but the historical approach seemed to lapse in the succeeding decades. In 1989 a more coordinated approach was initiated with the formation of the International History, Philosophy and Science Teaching Group (IHPST). At this time Kauffman (1989) wrote a review article on the status of history in the chemistry curriculum in which he summarised the advantages and the disadvantages of using the historical approach. The advantages listed maintained that a study of chemistry in an historical context highlighted chemistry as a human enterprise, as a dynamic process rather than a static product, as depending on interrelationships between historical events, as often multidimensional in its discoveries, as a discipline with strengths and limitations and as depending on intuition as well as logic in its problem-solving activities. Kauffman (1989) also observed that on occasion an historical investigation has assisted the chemist in their current research. The discovery of the noble gas, argon, is quoted as an example (see also Giunta 1998). Lord Rayleigh and Sir William Ramsay published their discovery of argon in 1895 (Rayleigh and Ramsay 1895). Small anomalies found in measurements of the density of nitrogen samples prepared by different methods and the unexplained existence of a residue in Cavendish's (1785) experiments on the passing of electricity through air a century earlier led to the discovery.

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The disadvantages of using the history of chemistry included the fact that there is a fundamental difference in goal and method between chemistry and history. While chemistry, like other sciences, abstracts, idealises, models and simplifies, history attempts to capture the richness of past events in their complexity. In spite of this difference, Kauffman challenges the reader ‘to attempt to present to the student a harmonious balance between the two’ (Kauffman 1989, p. 86). It is this harmonious balance between chemistry and history that is controversial amongst some professional chemists. If chemistry instruction is designed to enhance the practical skills of the chemist in a number of laboratory settings, for example, one might be able to successfully argue against the inclusion of chemical history in such instruction. If one’s purpose, on the other hand, is to educate the student in the broader context of knowledge development and validation, then history is an essential component of chemistry education at the secondary and tertiary level. This would also apply whether the student was studying chemistry as a major discipline or whether the student was a nonmajor in chemistry. Niaz and Rodriguez (2001) argue, however, that history is not something that is added to chemistry. It is already inside chemistry as it were. According to this view, it is difficult to teach chemistry either for skills or understandings without interfacing with its history in some form.

A second disadvantage revolves around the difficulty associated with assessing material that is both historical and chemical. Students, by nature, tend to only take seriously material that is assessed, but the question is how this should be done. Another two disadvantages concern the inappropriate use of a distorted history, often called ‘Whig’ history, and the likelihood that young students might feel estranged from the study of chemistry when they learn that chemists have not always ‘behaved as rational, open-minded investigators who proceed logically, methodically, and unselfishly toward the truth on the basis of controlled experiment’ (Kauffman 1989, p. 87). Kauffman (1989) finally discussed briefly four approaches to incorporating history into the chemistry curriculum: the *biographical approach*, the *anecdotal approach*, the *case study approach* and the *classic experiments approach*.

Thirteen years after Kauffman’s review, Wandersee and Baudoin-Griffard (2002) contributed a chapter on the history of chemistry in chemical education in a book dedicated to an appraisal of the status of chemical education at the beginning of the twenty-first century. It is interesting to ponder what similarities and differences in perception might be evident in these contributions over this 13-year period. Both articles identify the role of history in teaching about the nature of science (NOS) although by 2002 NOS had developed into a significant research area, whereas in 1989 it was only in the emergence phase. Wandersee and Baudoin-Griffard (2002) give more attention than did Kauffman (1989) to matters associated with student learning such as the comparison of student conceptions with early conceptions in the history of chemistry, the idea of meaningful and mindful (transferable) learning in understanding chemistry and some evidence that supports the notion that exposure to some history of chemistry enhances the learning of chemistry. Wandersee and Baudoin-Griffard (2002), like Kauffman (1989), deal with approaches to incorporating history into the chemistry curriculum, but they focus on Interactive

Historical Vignettes which are ‘a series of lively, carefully crafted, brief (~15 min), interactive’ (Wandersee and Baudoin-Griffard 2002, p. 34) stories tailored to the chemical concepts being studied. These authors lament the fact that only anecdotal evidence is available as of 2002 for the effectiveness of this approach to chemistry teaching and learning.

There has continued to be a burgeoning literature on this topic since 2002 to the extent that a process of categorisation is almost mandatory if one is to make any sense of the research in the field. It has therefore been decided to review the literature using five focus categories: (1) Student Learning, (2) Conceptual Clarity and Development, (3) Chemical Epistemology and the Nature of Science, (4) Pedagogy and Curriculum, and (5) Human Biography. While a large number of articles will deal with more than one of these categories, they will be discussed largely under the category which represents the major focus of the article.

11.2 Student Learning

When one considers the relationship between the history of chemistry and the learning of chemistry, there are two major considerations addressed by the literature. Firstly, there is an interest in the extent to which student conceptions in chemistry mirror those of the early scientists (Piaget and Garcia 1980). Secondly, there is an interest in whether the incorporation of the history of chemistry within chemistry teaching and learning has an impact on chemistry achievement.

The interest in comparing student conceptions with those possessed by scientists or chemists in the past has to do with the capacity of this scholarship to alert teachers to the kinds of thinking patterns of students that might present some resistance to change. Being aware of the history of the concept may provide clues that can assist the teacher in promoting conceptual change. While science educators agree that this might be achievable in some circumstances, they doubt that this can be achieved in all circumstances. It has been noted that ‘Students’ conceptions with limited empirical foundation…. have a completely different ontological status to empirically based ideas that are carefully formulated and sharpened by debate among scientific peers’ (Scheffel et al. 2009, p. 219). Given this proviso these workers examined the significance of student conceptions in the light of current and historical knowledge in the areas of the particulate nature of matter, structure–property relations, ionic bonding, covalent bonding and organic chemistry and macromolecular chemistry. In the case of ionic bonding in crystals, the historical use of particle shape both edgy (Hauy 1743–1822) and ball-like (Hooke 1635–1703) to explain crystal shape was also found to exist in students’ thinking (Griffith and Preston 1992). On the other hand, in the case of the concept of isomerism, it was concluded that ‘The importance of isomerism in the history of science does not correspond to the importance of isomerism in school’ (Scheffel et al. 2009, p. 244), because students’ difficulties with the concept do not correlate with historical ideas (Schmidt 1992). This was also the case for the octet rule in covalent bonding (Taber 1997, 1998). Even though 'the number of concrete studies comparing historical ideas and students' conceptions is fairly low in chemistry education' (Scheffel et al. 2009, p. 220), there are some studies of importance outlined below.

A questionnaire study (Furio-Mas et al. 1987) of students' conception of gases was undertaken with 1,198 pupils aged 12–18 years in Valencia. It was shown that the majority of students tended to adopt an Aristotelian view of a gas in that they believed gases have no weight because they rise rather than fall. In addition, for chemical reactions involving gases as reactants or products, the students thought that mass was not conserved. Younger students adopted a pre-seventeenth-century nonmaterial view of a gas. Fifty-nine science major students enrolled in Chemistry I at a university in Venezuela were asked to respond to a problem which asked them to select which of four particle distribution models represented hydrogen gas at a lower temperature than the one shown in the problem (Niaz 2000a). The most common distribution chosen was that which resembled a 'lattice' structure similar to that understood by scientists before the random distribution model deduced from the kinetic theory of gases in the nineteenth century.

A questionnaire and interview study of 54 year eight Barcelona students' understanding of mixtures, compounds and physical and chemical properties (Sanmarti and Izquierdo 1995) revealed that a significant number assigned a material nature to properties like colour and taste, a view that was held from the sixteenth to the eighteenth century. For example, on observing the dissolution of blue copper sulphate in water, one student said, 'the blue colour of the crystal can leave and pass into the water' (Sanmarti and Izquierdo 1995, p. 361). When blue copper sulphate crystals were heated, the colour change was explained as 'the water evaporates, and when it evaporates it carries this (blue) substance (with it)' (Sanmarti and Izquierdo 1995, p. 361). Sanmarti and Izquierdo (1995) use the term 'substantialisation of properties' to describe this phenomenon.

Van Driel et al. (1998) undertook a study of chemical equilibrium with 120 students aged 15–16 in the Netherlands. Original papers by Williamson (1851–1854), Clausius (1857) and Pfaundler (1867) were used to compare students' written responses to a questionnaire and group oral responses on audiotape with the nineteenth-century historical understanding. The reasoning students used to explain the incompleteness of a chemical reaction resembled the reasoning used by scientists of the nineteenth century particularly when the corpuscular model was used. However, the 'explanations remained incomplete or naïve. The few students capable of giving adequate explanations…implemented statistical notions in their explanations, analogous to Pfaundler's explanation of 1867' (Van Driel et al. 1998, p. 195). Niaz obtained results on a chemical equilibrium study that showed 'that at least some students consider the forward and reverse reactions as a sort of chemical analogue of Newton's third law of motion' (Niaz 1995a, p. 19), that is, action and reaction are equal and opposite.

Cotignola and colleagues (2002) interviewed 31 volunteers from science and engineering courses, 2 years after having studied basic thermodynamics, about the energetic processes associated with material sliding down inclined planes. The students used the word 'heat' predominantly in their explanations and were not able to distinguish it from internal energy. The authors suggest that Clausius followed a similar course when developing the field of thermodynamics in 1850 by focussing on the difference between sensitive heat and latent heat. The students ideas were not as sophisticated of course.

Although the literature comparing historical chemical ideas with student conceptions is not extensive, as previously mentioned, the reader should be aware of the large body of research in the general area of student conceptions. Classic references such as the handbook entry by Wandersee et al. (1994) and those addressing chemistry conceptions[1] are worth reading to put the historical ideas reported here in perspective. Research techniques for diagnosing and interpreting student conceptions can be found in DiSessa (1993), Taber and Garcia-Franco (2010), and Treagust (1988, 1995).

Moving on now to our second point of interest, what can one say about the use of the history of chemistry and chemistry achievement? The literature is not decisive on this matter. Using an experimental and control group of 14-year-olds where the experimental group was given a substantial amount of historical material and taught the same science content as the control group who were not presented with the historical material, Irwin (2000) observed that there was no significant difference between the groups in their understanding of contemporary science content related to atomic theory and periodicity. This was in spite of the fact that the historical approach did portray the nature of science more realistically. However, Lin (1998) did a similar study with 220 eighth graders where the experimental groups studied the historical cases of atmospheric pressure and atoms, molecules and formulae. All experimental and control groups were given four questions requiring conceptual problem solving in the science content. The experimental group did significantly better in conceptual problem solving. Lin et al. (2002) achieved similar results with a group of 74 eighth graders for chemistry conceptual problem-solving ability. The different outcomes to the Irwin study may be due to the nature, not necessarily the validity, of the science content test instruments, and this is worth exploring in further research.

A related matter to that in the previous paragraph is the relationship between history of chemistry and chemistry assessment. Niaz and colleagues (2002) have attempted to show how chemistry might be assessed within the context of historical experiments. In the case of Rutherford's gold foil experiment, for example, a suggested assessment item might be: What might you have deduced if most of the alpha particles were deflected through large angles? Perhaps the relationship between history of chemistry and chemistry achievement might depend on how closely the chemistry content interfaces with the history. This issue requires a more sustained research effort during this decade.

11.3 Conceptual Clarity and Development

History lends itself to giving depth and clarity to concepts, but we know that there is often a compromise between such an approach and that which focuses on the relatively quick generation of an answer to a problem. De Berg (2008a) has discussed

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[1] For example, Andersson (1990), Garnett et al. (1995), Kind (2004), and Taber (2002).

this issue in terms of an approach which emphasises *conceptual depth* over and against *conceptual usefulness* for the chemistry concepts of *energy*, *heat and work*, *element*, *mole* and the *uncertainty principle*. Others (Holme and Murphy 2011) define the difference in terms of *conceptual knowledge* and *algorithmic knowledge*[2]. The *Journal of Chemical Education* publishes many articles which focus on the history of chemistry and its role in giving clarity to concepts. There are at least *eighty-five* such articles published from 2005 to June 2011. Many of these articles show their historical character by having a title commencing with the words 'The Origin of….' The majority of these papers were written by Professor William Jensen who occupies the chair for the History of Chemistry at the University of Cincinnati. Table 11.1 samples Professor Jensen's 'The Origin of….' titles from 2005 to June 2011 with the *Journal of Chemical Education* references included.

Let us take one example from Table 11.1, The Origin of the *s, p, d, f* Orbital Labels, to illustrate how useful these titles can be in enlightening the significance of the symbols we commonly use in chemistry to represent concepts. Jensen (2007a) shows that the symbols originated around 1927 and represented the different line series present in alkali metal spectra. These lines were distinguished using the adjectives *sharp*, *principal*, *diffuse* and *fundamental*. The symbols, *s*, *p*, *d* and *f* were thus taken from the first letter of the names of these four series of lines and applied to the description of electron orbitals because line spectra were attributed to electron transitions between orbitals. It appears that Friedrich Hund was the first to use this nomenclature.

A sampling of 2010, 2011 and some 2012 articles from the *Journal of Chemical Education* which use historical information to bring clarity to the concepts of chemistry, other than 'The Origin Series' in Table 11.1, is given in Table 11.2. Most yearly issues of the journal contain articles which could be classified into at least some of the eight categories in Table 11.2 and serve as a rich resource for chemistry educators. The processes of chemistry which lead to the products of chemistry, some of which are shown in Table 11.2, also have a rich history. For example, an historical approach to the process of distillation 'where the old is redeemed to complement the new' (Lagi and Chase 2009, p. 5) provides a deeper understanding of the separation process in a modern context.

Eric Scerri (2007, 2009) has devoted a large portion of his working life to bringing clarity to the so-called periodic law and the structure of the *periodic table*. Many of the issues such as the difference between thinking of an element as a *basic substance* or a *simple substance* and the concept of *reductionism* are philosophical in nature and will be dealt with in another chapter of the handbook. But Scerri also involves the history of the development of the periodic table to highlight:

1. The renewed importance of Prout's hypothesis particularly if one regards atomic number as an important building block of the elements. Prout's hypothesis proposed that all the elements were compound forms of hydrogen. Accurate atomic weight determinations cast some doubt on the hypothesis in the nineteenth

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[2] See Nakhleh (1993), Nakhleh et al. (1996), Nurrenbem and Pickering (1987), Pickering (1990), and Zoller et al. (1995) for earlier references.

Table 11.1 A sample of 'The Origin of ….' titles written by William Jensen from 2005 to June 2011 and published in the *Journal of Chemical Education*

Title	Reference
The Origin of the Bunsen Burner	(2005a), 82(4), p. 518
The Origin of the 18-Electron Rule	(2005b), 82(1), p. 28
The Origin of the Liebig Condenser	(2006a), 83(1), p. 23
The Origin of the Term 'Allotrope'	(2006b), 83(6), p. 838
The Origin of the s, p, d, f Orbital Labels	(2007a), 84(5), p. 757
The Origin of the Names Malic, Maleic, and Malonic Acid	(2007b), 84(6), p. 924
The Origin of the Polymer concept	(2008a), 85(5), p. 624
The Origin of the Rubber Policeman	(2008b), 85(6), p. 776
The Origin of the Metallic Bond	(2009a), 86(3), p. 278
The Origin of the Circle Symbol for Aromaticity	(2009b), 86(4), p. 423
The Origin of the Ionic-Radius Ratio	(2010d), 87(6), pp. 587–588
The Origin of the Name 'Onion's Fusible Alloy'	(2010e), 87(10), pp. 1050–1051
The Origin of Isotope Symbolism	(2011), 88(1), pp. 22–23

Table 11.2 Historical examples from the *Journal of Chemical Education* (2010–2012) which clarify the concepts of chemistry

Chemistry profile	Examples	Reference
The products of chemistry	Synthetic dyes	Sharma et al. (2011)
	Quinine	Souza and Porto (2012)
The constants of chemistry	Avogadro's constant	Jensen (2010a)
	Atomic Mass, Avogadro's constant, mole	Barariski (2012)
The instrumentation of chemistry	pH meters	Hines and de Levie (2010)
The species of chemistry	Hydrogen ion	Moore et al. (2010)
The laws of chemistry	First law of thermodynamics	Rosenberg (2010)
	Thermodynamics-globalisation and first law	Gislason and Craig (2011)
	Clausius equality and inequality	Nieto et al. (2011)
The symbols of chemistry	R (organic), q, Q (thermodynamics)	Jensen (2010b), (2010c)
The models of chemistry	Bohr-Sommerfeld	Niaz and Cardellini (2011)
	Electronegativity	Jensen (2012)
The phenomena of chemistry	Fluorescence and phosphorescence	Valeur and Berberan-Santos (2011)

century, but a rehabilitation of the hypothesis became possible in the twentieth century based on the concept of atomic number.

2. The significance of the atomic number *triads* in developing a structure for the periodic table. The best form for representing the periodic table is still a matter of dispute. This fact is commonly not recognised by chemists. Scerri (2009) currently favours a form based on the atomic number triad which leads to a very symmetrical table with four groups to the left and four groups to the right of the transition series. The third and fourth transition series should commence with the elements lutetium and lawrencium rather than lanthanum and actinium on

Table 11.3 Some key chemistry concepts discussed in the journal *Science & Education* from an historical perspective including some references

Key chemistry concept	Reference
Gas laws	de Berg (1995), 4(1), pp. 47–64; Woody (2011) online first 6/12/11
Atomic theory	Chalmers (1998), 7(1), pp. 69–84
	Sakkopoulos and Vitoratos (1996), 5(3), pp. 293–303; Viana and Porto (2010), 19(1), pp. 75–90
Work, kinetic and potential energy	de Berg (1997a), 6(5), pp. 511–527
Kinetics	Justi and Gilbert (1999), 8(3), pp. 287–307
Electrolytic dissociation	de Berg (2003), 12(4), pp. 397–419
Acid–base equilibria	Kousathana et al. (2005), 14(2), pp. 173–193
Osmotic pressure	de Berg (2006), 15(5), pp. 495–519
Quantum mechanics	Hadzidaki (2008), 17(1), pp. 49–73
Heat and temperature	de Berg (2008b), 17(1), pp. 75–114
Mole concept	Padilla and Furio-Mas (2008), 17(4), pp. 403–424
Chemical equilibrium	Quilez (2009), 18(9), pp. 1203–1251
Electrochemistry	Eggen et al. (2012), 21(2), pp. 179–189

the basis of the atomic number triad but, this is still controversial. Published periodic tables as late as 2010 (e.g. Atkins and de Paula 2010) have not yet taken Scerri's suggestion seriously enough to change the format.

3. The illusions accompanying the nature of the periodic table. Significance is often given to Mendeleev's successful predictions of unknown elements, but it is rarely mentioned that only about 50 % of his predictions proved correct. The number of outer shell electrons is often used as the basis for the assignment of an element to a vertical group of the table. However, there are exceptions to this rule. Helium has the same number of outer shell electrons as the alkaline earth metals but is normally placed with the noble gases because of its inert characteristics. Nickel, palladium and platinum are in the same vertical group but have a different outer shell electron configuration.
4. The fact that the periodic system was discovered essentially independently by six scientists. Of these six, Mendeleev has been given the greatest credit for various reasons even though it could be argued that the German chemist Lothar Meyer was the first to produce, in 1864, a mature periodic system which was even more accurate than that produced by Mendeleev in 1869.

The journal, *Science & Education*, is dedicated to conceptual clarity through the lens of history and philosophy. A summary of some of the key concepts in chemistry which have been addressed in this journal is given in Table 11.3.

Some key chemistry concepts such as work and energy, fundamental to an understanding of thermodynamics, contain mathematical formulations of rich historical significance. For example, de Berg indicates that:

> the mathematical relationship, $mgh = \frac{1}{2} mv^2$, for free fall, could have been known from the time of Galileo and Newton….but the physical significance of the equation was not recognized till the early 19th century. That is, while the mathematics was in place by the 17th

> century, the fact that ½ mv^2 and mgh were measures of fundamental quantities was not known for 200 years. The physical notions of mechanical action (work) and force of a body in motion (kinetic energy) had separate historical developments…(but) their relationship (was finally) recognized in the 19th century and ultimately this paved the way for the development of the general concept of energy. (de Berg 1997a, p. 515)

The historical approach to the mathematical equations associated with chemistry concepts adds physical and conceptual significance to the equations beyond their algorithmic value.

11.4 Chemical Epistemology and the Nature of Science

How a chemist forms and validates chemical knowledge is central to an understanding of the nature of chemistry or chemical literacy. There is some debate about what is meant by the terms ‘chemical literacy’ and ‘nature of chemistry’ or the more general expressions ‘scientific literacy’ and ‘nature of science’. For example, McComas et al. (1998) isolated what they considered to be 14 consensus statements regarding the nature of science (NOS), Abd-El-Khalick (1998, 2005) suggested seven statements, and Niaz (2001b) used eight statements. Unanimity of opinion is hard to reach when it comes to defining NOS. A useful summary of the issues is given by Lederman (2006).

Some authors claim that a study of the history of chemistry enhances an understanding of the NOS. For example, Irwin (2000) exposed an experimental group of 14-year-olds to historical episodes associated with the concept of the atom and the periodicity of the elements and found gains, compared to a control group, in understanding aspects of the nature of science such as the usefulness of theories even when there may be some uncertainty about the validity of a theory. Lin and Chen (2002) observed that pre-service chemistry teachers’ understanding about the NOS was promoted by a study of the history of chemistry. In particular, the experimental group had a better understanding of the nature of creativity, the theory-based nature of scientific observations and the functions of theories. However, Abd-El-Khalick and Lederman (2000) found that coursework in the history of science (included atomic theory) does not necessarily enhance students’ and pre-service science teachers’ views of the NOS unless specific aspects of the NOS are also addressed.

Rasmussen (2007) has suggested that exposure to the history of chemistry in general chemistry classes can help students identify pseudoscientific attitudes in advertising. For example, the suggestion is made that introducing students not only to our current understanding of matter but to understandings held over centuries, some of which were erroneous, helps students address such assignment tasks as:

> A favourite claim of many advertisers is that their product is all-natural and thus contains no chemicals. In terms of our class lectures, explain why this is or is not a valid claim. (Rasmussen 2007, p. 951)

Giunta (2001) also focuses on errors that have surfaced in the development of chemical knowledge but from the point of view of the value that erroneous theories, such as the phlogiston theory, have played in furthering our knowledge of chemistry. Dalton's atomic theory, while containing some misplaced ideas according to our current knowledge, was an important stepping stone in leading to the concept of atomic weight. On the other hand, Giunta (2001) shows how a correct hypothesis such as Avogadro's hypothesis was rejected by a number of chemists at the time it was proposed for understandable reasons. The diatomic molecule proposal did not prove compelling enough to chemists to warrant acceptance of Avogadro's hypothesis. Giunta observes that 'the right hypothesis languished or at least struggled for decades' (Giunta 2001, p. 625). This illustrates how difficult it is for the scientific community to transition from one scientific model to another.

The notion of errors in the production of knowledge leads naturally into the significance of historical controversies in the progress of scientific knowledge.

De Berg (2003) has outlined the issues which were involved in the controversy between the Arrhenius School and the Armstrong School at the close of the nineteenth century in relation to the interpretation of what happens at the molecular level when a salt is dissolved in water, the so-called electrolytic dissociation controversy. One of the interesting factors associated with this controversy is the orientation taken to anomalous data. In the data produced by Raoult (1882a, b, 1884), it was clear that the molecular lowering factor associated with freezing point depression for sodium chloride (35.1) was close to double that for ethanol (17.3) and that for calcium chloride (49.9) close to three times that for ethanol. This data was consistent with the electrolytic dissociation hypothesis. The molecular lowering data for magnesium sulphate (19.2) and copper sulphate (18.0) proved anomalous however. One would have expected values close to those for sodium chloride (35.1) if the electrolytic dissociation hypothesis was applicable.

Fortunately these anomalies were held in suspension until they were explained in terms of the production of ion pairs due to the strong charges associated with both cation and anion. Chemists have learnt how futile it is to dispense with theoretical models too early as anomalies often lead to new knowledge provided one is happy to hold them in tension for a period of time. Sometimes anomalies will lead to a new paradigm such as a view of the solid state which includes aperiodic quasicrystals which have a non-repeating pattern at the microscopic level. Until Nobel Laureate Dan Shechtman (Nobel Prize in Chemistry 2011) discovered these in 1982, it was thought that one could not have a crystal without the existence of a repeating pattern of atoms. Controversy highlights how important it is for students to see chemistry as a human enterprise (Niaz 2009). It also indicates the dynamic nature of chemical knowledge, a point emphasised by modern philosophers of science (Machamer et al. 2000).

Chemical history can also be helpful in showing how the knowledge of a particular chemical compound has changed and progressed over time. De Berg (2008c, 2010) has illustrated the strength of this approach using the compound, tin oxide. One can discuss the chemistry of tin oxide over the three periods of chemical revolution described by Jensen (1998a, b, c): the period associated with the determination of chemical composition (1770–1790) at the macroscopic level, at the microscopic level (1855–1875) and finally at the electronic level (1904–1924). The nature of the chemistry associated with the development of an understanding of tin(IV) oxide in particular is shown by de Berg (2010) to involve, progressively from about 1800 to the present, descriptive chemistry, compositional studies, structural studies and advanced materials research. This kind of study gives a deep perspective to current research and might be one way of attracting more practising chemists to take an interest in the history of their subject.

When it comes to the development of a new chemical compound or a commercially viable form of a known compound, one must not forget the role that developments in the broader community such as that in economics, politics, technology and industry play in such developments. Coffey (2008, Chaps. 4 and 6) gives an insightful historical background to the commercial manufacture of ammonia by Haber and Bosch in the early twentieth century. What made the discovery so crucial was the perceived impending famine about to strike in Britain and Europe and its relief through the use of ammonia for the fertiliser industry. Ammonia was also earmarked for its role in the explosives industry, particularly at the onset of war in Europe. Chemical compounds can save lives; but they can unfortunately also take lives.

What is interesting about the historical approach to a discipline is how history pinpoints changes in the nature of discipline knowledge itself. In chemistry, for example, this is particularly noticeable in the way chemists described chemical reactions. In the case of combustion reactions, Joseph Priestley applied the phlogiston model for understanding the chemical change. The heating of a metal in air resulted in the release of phlogiston (the inflammability principle) from the metal to produce the calx. The concept of ‘principle’ was important in chemistry up until the end of the eighteenth century, although it did retain some use into the nineteenth century, so that chemists talked about the inflammability principle, the acid principle, the alkaline principle, the electrical principle, the magnetic principle and so on. Toward the end of the eighteenth century, however, Antoine Lavoisier claimed it was better to think of combustion of a metal in air as a chemical combination of the metal with the oxygen in the air. Chemical reactions were increasingly described in terms of atoms, ions and molecules rather than in terms of ‘principles’. The Priestley-Lavoisier debate as a debate in terms of the nature of chemical knowledge is discussed by de Berg (2011).

11.5 Pedagogy and Curriculum

One way of describing chemistry curricula is to examine the textbooks used by teachers and students. It is not surprising then that chemistry textbooks have been targeted as a source of research into chemistry curricula. In particular, the focus here will be on the way chemistry history is portrayed and used in chemistry textbooks. Van Berkel, De Vos, Verdonk and Pilot regard textbook chemistry as portraying what Kuhn (1970) would have called ‘normal science’ in that 'normal chemistry education is isolated from common sense, everyday life and society, history and philosophy of science, technology, school physics and from chemical research' (Van Berkel et al. 2000, p. 123). The general tenor of the research on chemistry textbooks has been rather critical of the portrayal and use of history when it has appeared, and more detail will be given in another chapter of the handbook. For the purposes of this section, some of the studies are summarised in Table 11.4 below.

Three of the references in Table 11.4 show how chemistry was portrayed in early textbooks, and it was often the case that the textbook was the main source of chemical information. France was the centre of the 'new chemistry' or the 'chemical revolution' with Lavoisier's influence predominating, and it is interesting to observe how this new chemistry was incorporated into textbooks of the era. Early textbooks of the twentieth century such as Partington's (1953) *Textbook of Inorganic Chemistry* contain significant amounts of historical material compared with later twentieth-century textbooks.

Researchers tend to be critical of more recent textbooks of chemistry either for the lack of historical material or for the way the historical material is presented. For example, Niaz (2000b) observed that, in discussing the oil drop experiment, the authors of chemistry textbooks did not give adequate treatment to the Millikan-Ehrenfest controversy. The oversimplification of the description of the experiment gives students the impression that the oil drop experiment yielded results with ease and without controversy. Holton (1978) has described how difficult this experiment was to perform and interpret. There are difficulties even when using modern apparatus (Klassen 2009). The question arises as to whether textbook authors can be expected to deal with historical material to the satisfaction of the historian or the chemist interested in history as well as presenting current trends in the subject. One option is to look at presenting the historical material in other ways.

Table 11.4 Some studies relating to the use of the history of chemistry in chemistry textbooks

Targeted chemistry concept	Reference
Covalent bonding	Niaz (2001a)
Models of the atom	Justi and Gilbert (2000)
Gases	de Berg (1989)
Electrochemistry	Boulabiar et al. (2004)
Periodic table	Brito et al. (2005)
Oil drop experiment	Niaz (2000b), Niaz and Rodriguez (2005)
Chemical revolution—late eighteenth century/early nineteenth century	Bertomeu-Sanchez and Garcia-Belmar (2006)
Chemical theories—late eighteenth century and early nineteenth century	Seligardi (2006)
Atomic structure	Niaz and Rodriguez (2002)
Aims and scope of chemistry in seventeenth-century France	Clericuzio (2006)
Amount of substance and mole	Furio-Mas et al. (2000)

Hutchinson (2000) has taken the concepts typically taught in general chemistry in university courses and expressed them in terms of nine case studies. For example, Case Study 3 on 'Periodicity and Valence' 'uses the experimental facts which were actually used to develop these concepts, and so introduces an historical perspective to their learning' (Hutchinson 2000, p. 4). This approach to experimental data is used in all the case studies. The purpose of the case studies is to teach chemistry not history, but historical experiments are used to show students how concepts are developed and models are built and how to distinguish between the data and its interpretation. In relation to models and theories, Hutchinson counsels that:

> It is very important to understand that scientific models and theories are almost never *proven*, unlike mathematical theorems. Rather, they are logically developed and deduced to provide simple explanations of observed phenomenon. As such, you will discover many times in these Case Studies when a conclusion is not logically required by an observation and a line of reasoning. Instead, we may arrive at a model which is the simplest explanation of a set of observations, even if it is not the only one. (Hutchinson 1997, Preface)

This curriculum is used for general chemistry at Rice University.

Niaz (2008) has written a book entitled, *Teaching General Chemistry: A History and Philosophy of Science Approach*, which can be used as a companion text to the student textbook by teachers. The emphasis is on conceptual problem solving in contradistinction to algorithmic problem solving and is based on the premise that the difficulties students face in conceptualising problems are similar to the difficulties scientists of an earlier period in the history of chemistry faced. The general chemistry concepts featured in the text include the mole, stoichiometry, atomic structure, gases, energy and temperature and chemical equilibrium. The text draws heavily upon research data related to student understanding of chemistry concepts. The approach is best illustrated by an example. In the chapter on gases, Niaz defines his approach as follows:

> The main objective of this section is to construct models based on strategies students use to solve the gas problems and to show that these models form sequences of progressive transitions similar to what Lakatos (1970) in the history of science refers to as progressive 'problemshifts'. Guideline 1 (defined in his chapter 3) suggests a rational reconstruction of students' understanding of gases based on progressive transitions from the 'algorithmic mode' (work of Boyle and others in the 17th century) to 'conceptual understanding' (work of Maxwell and Boltzmann in the 19th century). Results reported here are from Niaz (1995b). (Niaz 2008, p. 67)

The results of a study of the responses of sixty (N = 60) freshmen chemistry students to two items testing an understanding of gases are then discussed. The two items are shown below.

Item A

A certain amount of gas occupies a volume (V_1) at a pressure of 0.60 atm. If the temperature is maintained constant and the pressure is decreased to 0.20 atm, the new volume (V_2) of the gas would be:

$$(a)\, V_2 = V_1/6 \quad (b)\, V_2 = 0.33\, V_1 \quad (c)\, V_2 = V_1/3 \quad (d)\, V_2 = 3\, V_1$$

> *Item B*
> An ideal gas at a pressure of 650 mmHg occupied a bulb of unknown volume. A certain amount of the gas was withdrawn and found to occupy 1.52 mL at 1 atm pressure. The pressure of the gas remaining in the bulb was 600 mmHg. Assuming that all measurements were made at the same temperature, calculate the volume of the bulb (Niaz 2008, p. 68).

Niaz considers that *Item A* involves algorithmic problem solving and *Item B* conceptual problem solving. It was observed that 87 % of the students solved *Item A* correctly, whereas only 7 % of the students solved *Item B* correctly. The remaining students gained only partial credit for their answers. Niaz proposes that:

> Based on (the) strategies used in solving *Items A* and *B* it is plausible to suggest that students go through the following process of progressive transitions…
>
> Model 1: Strategies used to solve *Item A* correctly, that is, ability to manipulate the three variables of the Boyle's Law equation ($P_1V_1 = P_2V_2$) to calculate the fourth (N = 52).
>
> Model 2: Strategies used to correctly identify the final volume in *Item B*, that is, partial conceptualization of the property of a gas when it is withdrawn from a vessel (N = 16).
>
> Model 3: Strategies used to correctly identify and conceptualize two properties of a gas (final volume and pressure in *Item B*), when it is withdrawn from a vessel (N = 13).
>
> Model 4: Strategies used to correctly identify and conceptualize all the variables of a gas (*Item B*) when it is withdrawn from a vessel (N = 4). (Niaz 2008, p. 68)

In Model 4, it could also be considered that a strategy involving the additive property of 'amount of gas' where 'amount of gas' was understood as either mass, moles or particle number is important. The particle model of a gas, endemic to kinetic theory, leads to this conclusion.

Another strategy for incorporating the history of chemistry in chemistry curricula is the development and use of what de Berg (2004) calls a pedagogical history. A pedagogical history combines a knowledge of chemistry, history of chemistry, student learning and philosophy of science to develop an instructional storyline which requests students to engage with the text. Where possible, students are asked to interact with historical experimental data and to make decisions about how well the data fits the model. For example, in the case of the electrolytic dissociation model, students are presented with a table of molecular lowering factors from historical sources and asked two questions as follows:

Question 1
Which data do you think fits the model and which data, if any, doesn't fit the model?

Question 2
Now assess, in your view, how strongly the data in the table supports an ionic dissociation model.

The table of data contained some anomalous results although it is true that the majority of the data supported the model, but students had to decide which pieces of information were anomalous and to wrestle with the concept of the weight of evidence. Student reactions to some pedagogical histories have been published, (de Berg 1997b) and the issues involved in selecting the historical data to include in a pedagogical history are presented in a publication dealing with the case of the concepts of heat and temperature (de Berg 2008b).

11.6 Human Biography

Arguments for including history of chemistry in chemistry teaching and learning have always included the thought that history humanises chemistry. To humanise chemistry, however, we need to know something about the life story of the chemists involved, that is, their human biography. It has been maintained that:

> There is particular value in viewing the historical aspect of chemistry through a study of the lives of important chemists because the development of chemical concepts can then be seen in the context of the experiences of fellow human beings……In essence, the students learn that the development of science is a function of the people who develop it and the environment in which they live. (Carroll and Seeman 2001, p. 1618)

Carroll and Seeman (2001) describe how they incorporated scientific autobiography into a senior undergraduate course in advanced organic chemistry. Students studied the autobiography of the organic chemist, Ernest L. Eliel, and five of his key articles published over a period of 40 years. Collaborative group work and oral presentations were a feature of the methodology used. One student commented that 'Learning about Eliel's life caused me to be more interested in understanding the chemistry in the journal articles. We were able to see how the logical progression of his scientific research coincided with his life' (Carroll and Seeman 2001, p. 1620).

While Carroll and Seeman (2001) combined a study of a chemist's life story with a study of five of his most important chemistry publications at the senior undergraduate level, they suggested that a softer approach is probably better at the introductory level. The use of interesting 'incidental information' was recommended which 'can help make a human connection with the abstract concepts and does not require much class time' (Carroll and Seeman 2001, p. 1619). In Table 11.5 some examples of 'incidental information' for a range of chemists has been assembled with some important biographical references.

Table 11.5 Incidental information for a range of chemists along with important biographical references

Chemist	Incidental information	Biographical reference
Robert Boyle (1627–1691)	Very rich; wore a wig; never married; had an interest in alchemy and the turning of base metals into gold; had poor eyesight; intensely religious and supported the translation of the bible into different languages	Hunter (2009)
Joseph Priestley (1733–1804)	Discovered dephlogisticated air (oxygen); used his wife's kitchen as a laboratory; had a speech impediment but taught oratory; his house was burnt down because of his sympathies with the American and French Revolutions; was a dissenting minister; encouraged by Benjamin Franklin to take up science as a serious study	Matthews (2009) Schofield (1997, 2004)

(continued)

Table 11.5 (continued)

Chemist	Incidental information	Biographical reference
Michael Faraday (1791–1867)	Started work as a book binder; learnt chemistry from Humphry Davy; became famous for his chemistry demonstrations at the Royal Institution in London; gave us the names ‘anode’ and ‘cathode’ in electrochemistry; 96,500 coulombs per mole named after him	Williams (1965)
Dmitri Mendeleev (1834–1907)	Had 13 siblings; born in Siberia; his mother encouraged him to take up science; dynamic educator who attracted students from all faculties of the university to his lectures; fond of art; organised special classes in chemistry for women although he believed women to be inferior to men intellectually; famous for the periodic table; always pictured with a cigarette in his hand; believed in only getting his hair cut once a year	Byers and Bourgoin (1998) Scerri (2007)
Svante Arrhenius (1859–1927)	Swedish with stocky build, ruddy complexion, blonde hair and blue eyes; loved scientific controversy; his Ph.D. regarded as not of sufficient standard for an academic position but granted the Nobel Prize in chemistry in 1903 for his electrolytic dissociation theory; only married for a short time as his wife objected to his drinking and smoking; one of the first chemists to talk about the greenhouse effect	Crawford (1996)
Marie Curie (1867–1934)	Discoverer of the radioactive substance, radium; married Pierre; twice a Nobel Prize winner; 1903 shared Nobel Prize in Physics with husband Pierre and Henri Becquerel for work on radioactivity; won 1911 Nobel Prize in chemistry for discovering radium and polonium; had to work against gender bias; disapproved of fashion in dress; reared in poverty	Goldsmith (2005)
Martha Whiteley (1866–1956)	In a male-dominated field, she played a critical role on the academic staff of Imperial College London and secured admission of women chemists to the Chemical Society. She edited the multivolume Thorpe’s Dictionary of Applied Chemistry	Nicholson and Nicholson (2012)
Ernest Rutherford (1871–1937)	Country boy from the South Island of New Zealand; known for the development of simple but elegant experiments on the atomic nucleus; although not religious would sing ‘Onward Christian Soldiers’ with volume when an experimental breakthrough occurred; his ashes are buried in Westminster Abbey near that of Sir Isaac Newton	Campbell (1999) Reeves (2008) Wilson (1983)
Gilbert Lewis (1875–1946)	Famous for proposing the electron pair covalent bond and the octet rule; homeschooled entirely through elementary school; could read at age 3; learnt five languages; reserved in nature	Coffey (2008)

Table 11.6 A list of chemists discussed in the *Journal of Chemical Education* from the year 2000 to June 2011 along with the author reference

Chemist	Reference
Boerhaave (1668–1738)	Diemente (2000), 77(1), p. 42
Rutherford (1871–1937)	Sturm (2000), 77(10), p. 1278
Faraday (1791–1867)	Clark (2001), 78(4), p. 449
Pauling (1901–1994)	Davenport (2002), 79(8), p. 946
Mendeleev (1834–1907)	Marshall (2003), 80(8), p. 879
Priestley (1733–1804)	Williams (2003), 80(10), p. 1129
Bohr (1885–1962)	Peterson (2004). 81(1), p. 33
Porter (1920–2002)	Kovac (2004), 81(4), p. 489
Lavoisier (1743–1794)	Jensen (2004), 81(5), p. 629
Starkey (1628–1665)	Schwartz (2004), 81(7), p. 953
Boltzmann (1844–1906)	David (2006), 83(11), p. 1695
Haber (1868–1934)	Harris (2006), 83(11), p. 1605
Mendeleev (1834–1907)	Benfey (2007), 84(8), p. 1279
Boyle (1627–1691)	Williams (2009), 86(2), p. 148

Table 11.7 A sample of short biographies written by George Kauffman and published in the *Chemical Educator*

Chemist	Reference
Moses Gomberg (1866–1947)	(2008a), 13(1), pp. 28–33
Arthur Kornberg (1918–2007)	(2008a), 13(1), pp. 34–41 (with J. Adloff)
Antoine Henri Becquerel (1852–1908)	(2008b), 13(2), pp. 102–110
Frederic Joliot (1900–1958)	(2008c), 13(3), pp. 161–169
Fred Allison (1882–1974)	(2008b), 13(6), pp. 358–364 (with J. Adloff)
Gerald Schwarzenbach (1904–1978)	(2008d), 13(6), pp. 365–373
Dwaine O. Cowan (1935–2006)	(2009), 14(3), pp. 118–129
Osamu Shimomura (1928–)	(2009), 14(2), pp. 70–78 (with J. Adloff)
Alfred Maddock (1917–2009)	(2010a), 15, pp. 237–242 (with J. Adloff)
Marie and Pierre Curie (1859–1906)	(2010b), 15, pp. 344–352 (with J. Adloff)
Marie Curie (1867–1934)	(2011a), 16, pp. 29–40 (with J. Adloff)
Robert Bunsen (1811–1899)	(2011b), 16, pp. 119–128 (with J. Adloff)
John Bennett Fenn (1917–2010)	(2011c), 16, pp. 143–148 (with J. Adloff)
William Nunn Lipscomb (1919–2011)	(2011d), 16, pp. 195–201 (with J. Adloff)

From time to time, the *Journal of Chemical Education* will publish some useful and interesting biographical material on an important chemist. In Table 11.6 is recorded a list of chemists discussed in this journal from the year 2000 to June 2011. Some of the references report on an important book review.

George Kauffman writes short biographies of chemists for the *Chemical Educator* and a selection from 2008 to 2011 is shown in Table 11.7.

11.7 Conclusion

Much progress has been made in humanising the teaching and learning of chemistry through history since the first IHPST conference in 1989. However, measuring the impact of the history of chemistry on the teaching and learning of chemistry is still an area that needs further investigation. There appears to be no clear answer as far as academic achievement is concerned. Anecdotal evidence suggests that attitudes to and interest in chemistry can be improved by the historical approach, but well-planned research studies need to explore this possible relationship in more detail. We have noted some interesting ways that the history of chemistry has been used in chemistry curricula but if the impact is to be strengthened and grown, one will need to consolidate the history with the content of chemistry or, one might argue, to consolidate the current content with the history. I think that this will be the only way that teachers of chemistry will become convinced of the value of including an historical perspective. Clough (2009) has endeavoured to integrate history with content using thirty case studies, six of which are in chemistry. De Berg (2008c, 2010) has shown how history can embellish an understanding of a chemical compound from its antiquity to current research. Carroll and Seeman (2001) have shown how publications of a chemist from the embryonic stage of a career to the mature stage, that is, according to a chemist's historical journey, can be used to inform current chemistry content. These efforts have at least begun the journey of not only humanising but informing current content.

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Chapter 12
Historical Teaching of Atomic and Molecular Structure

José Antonio Chamizo and Andoni Garritz

12.1 General Introduction

> I can safely say that nobody understands quantum mechanics. R. Feynman (1985, p. 129)

The purpose of this paper is to argue that history and philosophy of chemistry and physics are central strategies in the teaching of atomic and molecular structure, from the Dalton model (for an earlier approach see Chalmers 1998) to modern quantum mechanics and quantum chemistry. Therefore, in addition to the presentation and conclusions, the chapter is divided into two equally important sections. The first describes the modern development of atomic and molecular structure, emphasising some of the philosophical problems that have confronted and been addressed by scientists, and those that have to be faced in understanding the science. The second discusses the alternative conceptions and difficulties that students of different educational levels bring to this subject and also the different approaches to the teaching of its history and/or philosophy. The conclusion is that a balance between the theoretical physicochemical basis of this chemistry knowledge and the phenomenological-empiricist knowledge must be achieved. But this cannot be done properly if teachers do not know and/or assume a particular historical-philosophical position.

Science education practice has not been driven to any great extent by research findings or by a goal of accomplishing professional ideals. The changes that have occurred in the majority of textbooks during the past decades do not show any real recognition of the growth in scientific knowledge (Schummer 1999). This is partly because of a chemistry teaching revolution 50 years ago (in the context of a revolution in the whole of science education: one which resulted from the Soviet success

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in launching Sputnik 1 in 1957). Under a philosophical (but hidden) umbrella, the change placed an emphasis on the physicochemical basis of General Chemistry in the three main projects of that decade: Chemical Bond Approach (Strong 1962), Chem Study (Campbell 1962) and Nuffield Foundation (1967).

The proposal was that the hegemony of physical chemistry would provide a basis of understanding for students' introduction to the chemical sciences through the quantum chemistry basis of the chemical bond, the kinetic model of the particulate nature of matter and the dominance of thermodynamics for explanations in several areas of chemistry. A new laboratory learning that promoted the notion of exploratory play with apparatus accompanied it. The General Chemistry course turned towards a theoretical character, losing the phenomenological approach that it had had in the preceding years. Without a deep recognition of its historical and philosophical roots, many people were led by this approach to believe that the contents of science textbooks were, in fact, science. But this is not necessarily true. The written materials employed in science education are descriptions of past science explorations (Yager 2004). Besides all this, once the majority of science teachers all over the world use textbooks as the main (sometimes the only) source of information—and the contents of the books have to expand in an idealised attempt to cope with the increase in information, with direct references to the history of sciences disappearing—they become, paradoxically and without wanting to …, history teachers! However, even if it was unconscious, it was a bad or a wrong way to teach the history of science. For example, Rodriguez and Niaz (2004) examined numerous textbooks for the History and Philosophy of Science (HPS) content in their approach to teaching atomic structure, and they found that an adequate and accurate reflection of the historical development is rarely presented.[1] This is educationally significant because philosophers of science and science education researchers have argued that quantum mechanics is particularly difficult to understand, due to the intrinsic obscurity of the topic and the controversial nature of its different interpretations [e.g. Copenhagen School "indeterminacy" (Bohr, Pauli, Heisenberg, Born, von Neumann and Dirac among others), Schrodinger with his cat paradox, the stochastic and the many world's interpretations and Bohm's "hidden variables" (Garritz 2013)].

12.2 The Subject Matter

12.2.1 Introduction

In this section a brief summary of several of the most important scientific advances of atomic and molecular structure, related mainly with chemistry but with a physicochemical character, will be presented. The starting point is Dalton's model of the atom and the whole nineteenth-century atomic controversy. At the end of that century, the 'discovery' by J. J. Thomson of negative corpuscles initiated the appearance of

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[1] See also Moreno-Ramírez et al. (2010).

Table 12.1 Some chapters of the book by C. J. Giunta (2010)

Author	Chapter name	Comments
W. B. Jensen	Four Centuries of Atomic Theory. An Overview	A description of the dominant flavour of atomic notions over the last four centuries from the mechanical through the dynamical, gravimetric and kinetic to the electrical
L. May	Atomism Before Dalton	Outlines a variety of atomistic ideas from around the world. It concentrates on conceptions of matter that are more philosophical or religious than scientific
D. E. Lewis	150 Years of Organic Structures	Fifty years after Dalton, F. A. Kekulé and A. S. Couper independently published representations of organic compounds that rationalise their chemistry and even facilitated the prediction of new compounds
W. H. Brock	The Atomic Debates Revisited	A description of episodes from the second half of the nineteenth century in which chemists debated the truth of atomic theory. Doubts about the physical reality of atoms led chemists to question the soundness of chemical atomism
C. J. Giunta	Atoms Are Divisible. The Pieces Have Pieces	Evidence for the divisibility continued and impermanence of atoms was collected even while some chemists and physicists continued to doubt their very existence
G. Patterson	Eyes to See: Physical Evidence for Atoms	By the early decades of the twentieth century, through the efforts of J. Perrin and others, scepticism over the physical existence of atoms was practically eliminated

models of structure within the atom, such as that of J. J. Thomson with Lord Kelvin. The nuclear model of Rutherford was followed by Bohr's model of stationary orbits, which applied the energy quantisation hypothesis of M. Planck, which, in turn, started the old quantum theory in 1900. Then, A. Einstein as an explanation for the photoelectric effect recognised the wave-corpuscular duality of light. All this old quantum theory was replaced by E. Schrödinger and W. Heisenberg's wave and matrix mechanics, respectively, following on from the pilot wave hypothesis of L. de Broglie, and after that chemical bonding was interpreted in the same terms of quantum mechanics.

On this issue it is important to note that in 2008 the American Chemical Society held a symposium entitled '200 Years of Atoms in Chemistry: From Dalton's Atoms to Nanotechnology' which was followed, a couple of years later, with the publication of a book with a similar name. For a quick view of the topic that is addressed here, some of its chapters with comments from the editor are shown in Table 12.1.

12.2.2 Dalton's Model. Nineteenth-Century Controversies Between Physicists and Chemists

Dalton's atomic model with associated relative atomic weights was constructed in 1805 to explain results on the absorption of gases into water (Chamizo 1992; Viana and Porto 2010). Since then, in the nineteenth and early twentieth centuries, several famous debates took place between atomists and anti-atomists (including some

Nobel Prize winners). The early contributions of scientists from several European countries as Berzelius, Gay-Lussac and Avogadro to the acceptance of this model were not enough to convince all chemists or physicists (Giunta 2010; Nash 1957). For example, Bensaude-Vincent indicates:

> It is well-known that French chemists were reluctant to adopt the atomic theory in the nineteenth century. Their opposition was long-standing and tenacious since the atomic hypothesis formulated in the first decade of the nineteenth century by John Dalton was banished from the teaching of chemistry until the early decades of the twentieth century. Instead of atomism, the French chemists preferred the Richter's language of equivalents because it avoided commitment to a speculative theory of indivisible elementary particles …[…]… There is a general agreement among historians of chemistry that this national feature was due to the overarching influence of positivism in France. (Bensaude-Vincent 1999, p. 81)

Following the Karlsruhe's Congress in 1861 (Kauffman 2010), most of the chemical community accepted the distinction between atoms and molecules with their respective atomic and molecular weights, as admirably shown by S. Cannizzaro. In general, atoms were regarded by physicists as inelastic or inertial points or particles. Meanwhile chemists accepted Dalton's model:

> A group of physicists, among them Ernst Mach, John Bernhard Stallo and Pierre Duhem began to voice doubts about physical atomism because the kinetic theory did not dovetail with accurate experimentation. …The consilience between chemistry and physics had broken down. Mach, in particular, believed science to be a construct of the human mind and that it was not possible to find independent evidence for the existence of matter. Influenced by the thoughts of Georg Helm in 1887, Ostwald began to deny atomism explicitly. He opted instead for energetics –the laws of thermodynamics– rather than mechanical explanations in chemistry. He argued that energy was more fundamental than matter, which he saw only as another manifestation of energy. It followed that chemical events were best analyzed as a series of energy transactions. The difference between one substance and another, including one element and another, was due to their specific energies. (Jensen 2010, p. 63)

A century had to pass before the atomic model was fully accepted, which can be marked by formal recognition of J. B. Perrin's researches at the Solvay Conference of 1911 (Giunta 2010; Izquierdo 2010; and Izquierdo and Adúriz 2009).

12.2.3 The Electron and Thomson's Atom Model

There was a controversy about the nature of cathode rays (German physicists supported the ether theory for their origin, while the British argued for their particle nature), but it was the discovery of X-rays in 1895 that triggered J. J. Thomson's interest in cathode rays. He conducted a series of experiments at the beginning of 1897, which were first presented at a Friday evening discourse of the Royal Institution on April 29, 1897, and were finally published at length in the *Philosophical Magazine* in October the same year.

Thomson points out a fundamental aspect of his experiments, namely, that cathode rays are the same whatever the gas through which the discharge passes, and concludes: '[cathode rays] are charges of negative electricity carried by particles of matter. The question that arises next is: what are these particles? Are they atoms, or molecules, or matter in a still finer state of subdivision?' (p. 302). That is why he determined the relation *m/e*. From which Thomson concluded that its value, 10^{-12} kg/C, is independent of the nature of the gas, and it is very small compared with the 10^{-8} kg/C of H^+, the hydrogen ion in electrolysis, which is the smallest value of this quantity previously known.

Thomson goes further and proposes an atomic model:

> Since corpuscles similar in all respects may be obtained from different agents and materials, and since the mass of the corpuscles is less than that of any known atom, we see that the corpuscle must be a constituent of the atom of many different substances (p. 90)… […]… The corpuscle, however, carries a definite charge of negative electricity, and since with any charge of negative electricity we always associate an equal charge of the opposite kind, we should expect the negative charge of the corpuscle to be associated with an equal positive charge of the other…we shall suppose that the volume over which the positive electricity is spread is very much larger than the volume of the corpuscle. (Thomson 1904, p. 93)

This model would last until Geiger and Marsden's experiment of bombarding metal thin films with radioactive particles, which allowed E. Rutherford to postulate the existence of the nucleus. On this subject we should mention the book *Histories of the Electron* that arose from two meetings (one in London and the other in Cambridge, Massachusetts) held to celebrate, in 1997, the centenary of the electron's discovery. The book is divided into the following four main sections that recognise the breadth of the subject being treated, and particularly the relations among the various sciences, and with technology and philosophy:

- Corpuscles and Electrons
- What Was the Newborn Electron Good For?
- Electrons Applied and Appropriated
- Philosophical Electrons

Some of its chapters with comments from the editors are shown in Table 12.2.

12.2.4 Planck, Einstein and Bohr: The Old Quantum Theory

The centennial of quantum theory has been celebrated a few years ago (Kleppner and Jackiw 2000). Quantum mechanics forced physicists and chemists to reshape their ideas of reality, to rethink the nature of things at the deepest level and to revise their concepts of determinacy vs. indeterminacy, as well as their notions of cause and effect.

The clue that triggered the quantum revolution came not from studies of matter but from a problem in radiation. The specific challenge was to understand the spectrum of light emitted by black bodies (that absorb and emit all kinds of electromagnetic radiation). In M. Planck's seminal paper (1900) on thermal radiation, it was hypothesised that the total energy of a vibrating system cannot be changed continuously. Instead, the energy must jump from one value to another in discrete steps, or

Table 12.2 Some chapters of the book by Buchwald and Warwick (2001)

Author(s)	Chapter name	Comments
I. Falconer	Corpuscles to Electrons	Thomson’s main accomplishment at the Cavendish Laboratory in the mid-1890s was to succeed in deflecting a beam of cathode rays electrostatically, something that continental experimenters had failed to do
H. Kragh	The Electron, the Protyle, and the Unity of Matter	Identifies four different kinds of electrons before 1900: the electrochemical, the electrodynamic, the one associated with cathode ray work and the magneto-optical. The underlying notion of the electron as a fundamental building block of matter appealed particularly to J. J. Thomson and several others, who often thought of the electron as a sort of chemical proto-substance
W. Kaiser	Electro Gas Theory of Metals: Free Electrons in Bulk Matter	By early 1900, metallic conduction had become a central feature of a burgeoning microphysical practice, one that in this case sought to unify electrodynamics of electric sources in metals, with the model of colliding particles that underlie the kinetic theory of gases
L. Hoddeson and M. Riordan	The Electron, the Hole and the Transistor	The use of the electron in the design of amplifiers and semiconductors not only produced the new discipline of electronics but eventually enabled the very absence of the electron in certain material structures to be reified as a new entity in its own right, the ‘hole’
M. J. Nye	Remodeling a Classic: The Electron in Organic Chemistry	In the broader historical picture, the arrival of the electron and quantum physics in chemistry was seen as fulfilling the expectations of men like Lavoisier and Dalton who were understood to have been the driving forces of the first chemical revolution
K. Gavroglu	The Physicists’ Electron and Its Appropriation by the Chemist	Where physics sought a single theory that, in principle, was analytically exact in all cases, chemistry, a primarily laboratory-based science, sought one or more models that were applicable to a wide range of empirical data
P. Achinstein	Who Did Really Discover the Electron?	The historical facts about who knew what and when are complex
M. Morrison	History and Metaphysics: On the Reality of Spin	The reality ascribed to entities is often the result of their evolution in a theoretical history. The history of belief intersects with the evolution of theoretical trajectories
N. Rasmussen and A. Chalmers	The Role of Theory in the Use of Instruments; or, How Much Do We Need to Know About Electrons to Do Science with an Electron Microscope?	The effective use of an instrument does not necessarily depend in any meaningful way on theories about the way in which the device functions. The electron microscope was fruitfully used in discovering the biological cell’s endoplasmic reticulum without a theory of how it interacted with the object

quanta, of energy. The idea of energy quanta was so radical that Planck let it lie fallow. A. Einstein (1906), then unable to obtain an academic position, wrote from the Swiss patent office in Berne: 'Analyzed in classical terms Planck's black-body model could lead only to the Rayleigh-Jeans law'. Kuhn (1978, p. 170) also made a contribution to this Planck-Einstein debate by saying that 'Planck's radiation law could be derived instead, but only by decisively altering the concepts its author had employed for that purpose'. Midway through his paper, Einstein wrote:

> We must therefore recognize the following position as fundamental to the Planck theory of radiation: […]. During absorption and emission the energy of a resonator changes discontinuously by an integral multiple of $h\nu$. Moreno-Ramírez et al. (2010)[2]

Delighted as every physicist must be that Planck in so fortunate a manner disregarded the need [for such justification], it would be out of place to forget that Planck's radiation law is incompatible with the theoretical foundations which provide his point of departure (Einstein 1909, p. 186).

More recently, in 1913, N. Bohr applied the quantisation to the angular momentum of the hydrogen atom and obtained the whole set of J. R. Rydberg's spectral frequencies (Heilbron and Kuhn 1969). Even then the concept was so bizarre that there was little basis for progress with this 'old quantum theory'. Almost 15 more years and a fresh generation of physicists were required to create modern quantum theory. For an interesting and detailed description of the historical details of all quantum discoveries, Baggott (2011) can be consulted.

12.2.5 De Broglie, Heisenberg and Schrödinger. Quantum Mechanics

In 1923, L. de Broglie tried to expand Bohr's ideas and he pushed for their application beyond the hydrogen atom. In fact he looked for an equation that could explain the wavelength characteristics of all matter. His equation, $\lambda = h/p$, in relation to the wavelength of particles was experimentally confirmed in 1927 when physicists L. Germer and C. Davisson fired electrons at a crystalline nickel target, and the resulting diffraction pattern was found to match the predicted value of λ. Also G. P. Thomson—son of Joseph John, the discoverer of the electron—corroborated the de Broglie's wavelength of electrons going through very thin films of metals. Whereas his father had seen the electron as a corpuscle (and won the Nobel Prize in the process), he demonstrated that it could be diffracted like a wave. That is why it is said that Thomson's family contributed to the wave-particle duality of the electron by occupying the lead positions on both sides.

A second pillar of the development of quantum mechanics was W. Heisenberg, who reinvented matrix multiplication in June 1925 with his 'matrix mechanics' as

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[2] In German he says 'Die Energie eines Resonators ändert sich durch Absorption und Emision sprungweise, und zwar ein ganzzahliges Vielfache von *$(R/N)\beta\nu$*' (Einstein 1906, p. 202).

was confirmed by M. Born and P. Jordan after revising his work. On May 1926, Heisenberg began his appointment as a university lecturer in Göttingen and with an assistantship to Bohr in Copenhagen. Heisenberg formulated the uncertainty principle in February 1927 while employed as a lecturer in Bohr's Institute for Theoretical Physics at the University of Copenhagen. He was awarded the 1932 Nobel Prize in Physics. In Bohr's words, the wave and particle pictures, or the visual and causal representations, are 'complementary' to each other. That is, they are mutually exclusive, yet jointly essential for a complete description of quantum events.

Next year the Nobel Prize was awarded to P. A. M. Dirac and E. Schrödinger. The great discovery of the latter, in January 1926, was published in *Annalen der Physik* as 'Quantisierung als Eigenwertproblem' [Quantization as an Eigenvalue Problem]. It was known as 'wave mechanics' and later as Schrödinger's wave equation. This paper has been universally celebrated as one of the most important achievements of the twentieth century, and created a revolution in quantum mechanics, and indeed of all physics and chemistry. On May that year Schrödinger published his third article, in which he showed the equivalence of his approach to that of Heisenberg's matrix formulation.

12.2.6 Kossel, Lewis and Langmuir; Heitler-London-Slater and Pauling; and Hund and Mulliken: Quantum Chemistry and Bonding Models

During World War I, in 1916, W. Kossel and G. N. Lewis (Lewis 1923) began independently to develop electronic models of chemical bonding, a concept fruitfully extended shortly thereafter by I. Langmuir. In the new models, the second and third periods of the periodic table each have eight members; the last of which (a noble gas) has a stable nonbonding 'octet' of electrons in a shell. Beyond the octet shells are the odd electrons in the outer shell, the 'valence electrons', which can be shared with adjacent atoms to form chemical bonds.

Langmuir expresses his view that the type of approach used by chemists is substantially different to that used by physicists:

> The problem of the structure of atoms has been attacked mainly by physicists who have given little consideration to the chemical properties, which must ultimately be explained by a theory of atomic structure. The vast store of knowledge of chemical properties and relationships, such as is summarized in the periodic table, should serve as a better foundation for a theory of atomic structure than the relatively meager experimental data along purely physical lines". (Langmuir 1919, p. 868)

In the late 1920s and early 1930s, W. Heitler, F. London, J. C. Slater and L. Pauling developed the 'valence-bond theory' as an application of the new quantum mechanics of E. Schrödinger and W. Heisenberg. Almost at the same time, R. Mulliken developed an alternative theory that began not from the electrons in atoms, but from the molecular structure ('molecular orbital' bonding). Partly because the extensive and vitally useful role of mathematics in physics had never been transferred to chemistry, it took until 1940 for Pauling and Mulliken theories to gain wide acceptance. The Nobel committee delayed 20 and 30 years, respectively, to honour this revolution. Pauling became laureate in 1954, and Mulliken won it in 1966 (Feldman 2001).

P. Atkins has recently presented his latest edition of the book on quantum chemistry with De Paula and Friedman (2008) as co-authors, where they review the latest improvements in making calculations. For example, they write on ab initio methods, configuration interaction and many body perturbation theories that were developed with the advent of high-speed computers in the 1950s. They proceed to density functional theory and its beginnings with Hohenberg and Kohn (1964) theorems and Kohn and Sham (1965) equations. Kohn was awarded the Nobel Prize for Chemistry in 1998. They then discuss a method for approximation of exchange (proposed by Slater (1951), a simplification that became known as the Xα method) and of correlation energies, introduced in the 1960s and 1970s. Their final section examines current achievements, including the impact of quantum chemistry methods on nanoscience (the structure of nanoparticles) and medicine (molecular recognition and drug design).

12.2.7 Molecular and Crystal Symmetry and Spectroscopy

Spectroscopy is the study of the interaction of electromagnetic radiation with matter. In 1860 the German scientists R. Bunsen and G. Kirchhoff discovered two alkali elements, rubidium and cesium, with the aid of the spectroscope they had invented the year before. Since then spectral analysis has been a central tool in chemistry, physics and astronomy. But it is not only spherical atoms that interact with light; molecules can also do it. Molecules may interact with the oscillating electric and magnetic fields of light and absorb the energy carried by them. The more symmetric the molecule, the fewer different energy levels it has and the greater the degeneracy of those levels. The study of symmetry helps us to simplify problems by reducing the number of energy levels one must deal with. But more than that, symmetry helps us decide which transitions between energy levels are possible and which are not (Harris and Bertolucci 1978) through selection rules, addressing problems that were possible to pose and solve via a branch of mathematics named group theory.

The history of group theory and that of quantum mechanics can be of great assistance in understanding the applications of spectroscopy to physical problems. Nobel laureate P. W. Anderson (1972, p. 394) wrote ‘it is only slightly overstating the case to say that physics is the study of symmetry’. While quantum theory can be traced back only as far as 1900, the origin of the theory of groups is much earlier. It was given definite form in the later part of the eighteenth and in the nineteenth centuries. F. Klein—a German mathematician, known for his work in group theory, function theory, non-Euclidean geometry and on the connections between geometry and group theory—considered the group concept as most characteristic of nineteenth-century mathematics.

The concept of a group is considered to have been introduced by E. Galois (1811–1832). Galois refashioned the whole of mathematics and founded the field of group theory only to die in a pointless duel over a woman before his work was published when he was 21 years old. J. Liouville published his ideas in 1846. Some aspects of group theory had been studied even earlier: in number theory by L. Euler, C. F. Gauss and others and in the theory of equations by A. L. Cauchy and J. L. Lagrange (each with a well-known group theory theorem).

At the heart of relativity theory, quantum mechanics, string theory and much of modern cosmology lies one concept: symmetry. In *Why Beauty Is Truth*, world-famous mathematician I. Stewart (2007) narrates the history of this remarkable area of study. He presents a timeline of discovery that begins in ancient Babylon and travels forward to today's cutting-edge theoretical physics.

The symmetry aspects are crucial today for the different models of chemical structure, bonds, spectroscopic interpretations and chemical reactions. In many of these problems the crucial problem is that of the potential seen by electrons moving in the electric field of the nuclei. The relation between science and mathematics resides in the commutation of the Hamiltonian with the symmetry operators, so that the wave functions of the atoms, or molecules, are bases of some of the irreducible representations of the point group to which the system belongs. Many books have appeared devoted entirely to applications of symmetry and aspects of group theory to chemistry. Examples include two classical books (Bishop 1973; Cotton 1963) and one modern (Hargittai and Hargittai 2009).

12.2.8 The Problem of Reduction of Chemistry into Physics

One of the most deeply entrenched traditions, which could be seen as an orthodoxy that extends beyond the scientific community to the whole of society, is that science can be explained in terms of the logical positivist philosophical tradition. Since the nineteenth century, logical positivism has sought to clearly establish a boundary between science and non-science using two additional criteria:

- An empirical-experimental approach (if something cannot be interpreted in terms of observations or measurements, then it is not scientific, it is metaphysical)
- A criterion of logical-mathematical inference and scientific theory (one aspect is that if something cannot be rebuilt in a deductive way, it is not rational, it is unscientific)

Logical positivism assumes the axiomatisation of theories unifying all sciences into one. In its most widely recognised version (Reish 2005), logical positivism, presenting science as a linear succession of successful discoveries and placing the emphasis on factual recall with confirmatory experiments, contributed to identify what kinds of research questions and issues were adequate. This programme of unification of science and deriving the principles of one science from another is commonly known as reductionism. The logical positivist assumes that the laws of a particular science, like chemistry, can in principle be derived from other more basic laws, in this case from physics. This position became stronger particularly with the development of relativistic quantum mechanics by P. A. M. Dirac. He indicated:

> The underlying laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that exact applications of these laws lead to quantum mechanical equations which are too complicated to be soluble. (Dirac 1929, p. 714)

One of the most important philosophers of science of the time, working from a logical positivist perspective, H. Reichenbach celebrated Dirac's claim, indicating that:

> The problem of physics and chemistry appears finally to have been resolved: today it is possible to say that chemistry is part of physics, just as much as thermodynamics or the theory of electricity. (Reichenbach 1978, p. 129)

A few years later, Reichenbach distinguishes between contexts of discovery and justification, an issue that has occupied a prominent place in the philosophy of science. Since then, in its best known version (Reish 2005), logical positivism has presented science as a linear succession of successful discoveries and has placed the emphasis on factual recall with confirmatory experiments. This contributed to identifying what kinds of research questions and issues were adequate for the axiomatic structure of science.

But in the 1960s, several science philosophers started to question the lack of historicity of logical positivism, which was based mainly in the context of justification (Reichenbach 1938). They proposed alternative ways of conceiving the philosophy of science based on historical ideas such as change, progress or revolution (Kuhn 1969; Toulmin 1961, 1972). More recently several philosophers have also questioned other traditional assumptions of logical positivism such as reductionism and verificationism (Hacking 1983; Harré 2004; Laudan 1997; Popper 1969). This indicates that the philosophy of science has escaped the constraints imposed by the context of justification without losing sight of the question of rationality. New and different ways of approaching the philosophy of science have emerged, for example, M. Christie and J. Christie (2000) make a case for the diverse character of laws and theories in the sciences and particularly consider a pluralistic approach to laws and theories in chemistry. R. Giere (1999) considers that science does not need laws because 'science does not deliver to us a universal a truth underlying all natural phenomena; but it does provide models of reality possessing various degrees of scope and accuracy' (Giere 1999, p. 6).

These new and different approaches to the philosophy of science lead to reconsideration of what Dirac said. Thus the Nobel Prize winner in Chemistry, for his theory concerning the course of chemical reactions using quantum mechanics, R. Hoffmann indicated (1998, p. 4):

> Only the wild dreams of theoreticians of the Dirac school make nature simple.

This idea was shared by the 1969's Physics Nobel Prize for his contribution and discoveries on the classification of elementary particles (quarks) and their interactions, M. Gell-Mann. He said (1994):

> When Dirac remarked that his formula explained most of physics and the whole of chemistry of course he was exaggerating. In principle, a theoretical physicist using quantum electrodynamics can calculate the behaviour of any chemical system in which the detailed

> internal structure of atomic nuclei is not important. [But:] in order to derive chemical properties from fundamental physical theory, it is necessary, so to speak, to ask chemical questions. (Gell-Mann 1994, p. 109)

And some of those chemical questions, perhaps the simplest, are related to the periodic table. Much has been written about them (Jensen 2002; Scerri 2007), but it is relevant to recall what philosopher of chemistry J. van Brakel (2000) says:

> As a specific example of the reduction of chemistry to physics, it is often suggested that the periodic table can be 'derived' from quantum mechanics. Such a reduction was already ascribed to Bohr, for example, by Popper. But, contrary to his own claims (and those of Popper) 'Bohr populated the electron shells while trying to maintain agreement with the known experimental facts'. Later developments too in quantum mechanics cannot strictly predict where chemical properties recur in the periodic table. Pauli's explanation for the closing of electron shells does not explain why the periods end where they do: the closing of shells is not the same as the closing of periods in the table. Unknown electronic configurations of atoms are not derived from quantum mechanics, but obtained from spectral observations. Hund's rule states an empirical finding and cannot be derived. (van Brakel 2000, p. 119)

A current periodic table shows many and various properties attached to atoms, including, for example, the size. However, the various theoretical approaches derived from quantum mechanics to calculate atomic size assume, arbitrarily, that atoms are bounded. There is no such thing as an absolute atomic size. An atom is not a rigid sphere, so 'atoms differ in size depending on the type of external forces acting on them' (Cruz et al. 1986, p. 704). The various experimental techniques used to determine internuclear distances indicate that the size of atoms depends on the surrounding environment. Therefore, a periodic table can only show covalent, ionic or metallic radii as typical outcomes from experimental measurements of many different solids.

As several researchers have discussed when addressing entanglement (Primas 1983), arising from strict quantum mechanical treatments, physical systems are never isolated nor closed. As with the size of atoms, so the geometry of molecules varies depending on their environment. Van Brakel indicated:

> According to Primas the crucial issue is not the approximations of quantum chemistry as the Born-Oppenheimer description, but the breaking of the holistic symmetry of quantum mechanics by abstracting from the Einstein-Podolsky-Rosen (EPR) correlations. It is the EPR correlations that exclude any classical concept of object, shapes or the fixed spatial structures such as presupposed in the notion of molecular structure … therefore, quantum chemistry borrows the notion of molecular structure from classical chemistry. (van Brakel 2000, p. 144)

R. G. Woolley (1978) defends this position in his famous and provocative article 'Must a molecule have a shape?' which indicates that the classic concept of molecule cannot be derived from quantum mechanics. Nevertheless, since the nineteenth century, chemists have determined experimentally the particular geometries of various molecules. Today we know that these geometries are relative to the timescale of measurement.

Thus, there are difficulties in interpreting even the simplest chemical phenomena, rigorously and independently, from quantum mechanics. The problems are almost intractable as can be recognised in Table 12.3 (Jensen 1980).

Table 12.3 Outline of steps which, according to our present knowledge of quantum mechanics and statistical thermodynamics, are necessary in order to predict rigorously the equilibrium or rate constant of a reaction in solution from first principles

1. Calculation of the electronic potential energy of the static arrangement of atoms corresponding to the structures of each reactant and product
2. Prediction of the normal modes of motion for the atoms in each structure. This amounts to setting up a mathematical description of the structure's vibrational and rotational motions
3. For many of these motions, the lowest kinetic energy is not zero, but rather a half-quantum of the motion. This zero-point kinetic energy must be added to the potential energy
4. From the knowledge of the normal modes of motion, it is possible to compute the partition function of each species as a function of temperature and from this is obtained the standard free energy and enthalpy of each species in the dilute gas state and at the temperature of interest
5. The standard free energy and enthalpy of each species in solution is then computed considering the transfer from the gas phase to solution
6. Values of ΔH^0 ΔG^0 and ΔG^* and ΔH^* are calculated for the maximum point on the surface of least energy connecting the reagents with the products. With these values it is possible to calculate the equilibrium constant and reaction rate
7. Finally the calculated values must be recalculated to consider the actual concentration of the various species in solution using the activity coefficient of each species for the temperature and solvent under consideration

For similar reasons there are many chemical notions that are not amenable to rigorous quantum mechanical treatment. Van Brakel (2000) mentions some of them: acidity, aromaticity, basicity, chemical bond, chemical reaction, chirality, electronic configuration, orbital, electronegativity, functional group, molecular structure, resonance, relative energy of *s* and *p* orbitals and valence.

In a similar way another philosopher of chemistry J. Schummer (1998) recognises the differences among the various sciences when dealing with the study of material properties (which from a reductive view are those of the atomic and molecular structure):

> For sciences of materials, with chemistry at the centre, have been, from the earliest stages on, experimental science in the original meaning of studying the behaviour of objects in various and controlled artificial contexts. A material property is reproducible behaviour within certain reproducible contextual conditions. It is important to note that material properties are attributed not to isolated objects but to objects and contexts. Since everything looks red under red light, we have to specify the colour both of the object under investigation and of the light, in order to make qualified colour statements. Since everything is solid at a certain temperature and pressure, solidness always implies specification of thermodynamic conditions. Sometimes it is more the context that matters. To speak of a toxic substance does not mean that the substance itself but the context, a biological organism, falls sick or dies, if it gets in contact with the substance. Precise material predicates require precise and systematic details of the contexts of investigation, making contexts themselves a central subject matter of sciences of materials.

This poses a difficult problem in the teaching of atomic and molecular structure, when it ignores its historical roots and philosophical consequences, an issue that has not escaped the experts. In 1999 *Nature* published a report that orbitals had been observed (Zuo et al. 1999). There were philosophical objections (Scerri 2000a, 2001), which indicated a confusion of the authors of this article aforementioned between observable and unobservable (Shahbazian and Zahedi 2006) and between the real world and models (Pagliaro 2010). The following quotes from some of the participants in this discussion help to clarify their positions, particularly in relation to the teaching of this topic:

> … chemists have a tendency to "decompose" molecules arbitrarily into basic conceptual or pseudo-physical components (such as orbitals and atoms), which can cause controversy. The entities, which come from such decompositions, make a new class of mathematical objects: "non-observables". Using these non-observables as a tool for chemical arguments is a common practice of chemists. (Shahbazian and Zahedi 2006, p. 39)

> Orbitals however are also a (quantum) chemical model of immense importance in chemistry. Their relationship to the chemical methodology is heuristic, i.e., their usefulness in many branches of science justifies the use of the model. (Pagliaro 2010, p. 279)

> Yes, it is important to know when approximations are made, but success in a science like chemistry is largely a matter of finding useful approximations: this is what students should be taught. (Spence et al. 2001, p. 877)

> Chemical educators should continue to use concepts like orbitals and configurations but only while recognizing and emphasizing that these concepts are not directly connected with orbitals as understood in modern quantum mechanics, but are in fact a relic of the view of orbits in the so-called old quantum theory. (Scerri 2000b, p. 412)

Finally, it is important to recognise that traditionally two types of reductionism have been considered: ontological and epistemological (Silberstein 2002). Despite the intense debates that have occurred in this area, where important issues are those related to 'the kind of relations', or 'the way in establishing relationships' (Lombardi and Labarca 2005), recent years have witnessed a growing consensus towards a tradition that denies the possibility of reducing chemistry to physics. In particular there is a denial that such a reduction has been achieved via quantum mechanics as considered from logical positivism. Bibliography related to this subject can be found in Erduran (2005), Schummer (2008), Snooks (2006), and Velmulapalli and Byerly (1999).

12.3 Procedures

12.3.1 Introduction

This section addresses three issues. The first has to do with the way that history and philosophy of sciences are incorporated into the teaching of atomic and molecular structure. The second considers the diversity of previous ideas that students from different educational levels bring to the subject and how these ideas hinder their learning. Finally, the third part outlines several reported experiences in teaching atomic and molecular structure. About all this M. Niaz has dedicated a book (Niaz 2009) and a full set of papers (e.g. Niaz 2000 and 2010) dedicated to posing the necessity of the historical teaching with episodes and experiments that have been important in science progress. He emphasises the validity of the following phrase of Kant and Lakatos: ‘philosophy of science without history of science is empty’.

12.3.2 Philosophy and History in Teaching and Their Importance

In present science education, history and philosophy play a fundamental role (Duschl 1994; Matthews 1994/2014; Wandersee and Griffard 2002). But the teaching of history cannot be only the chronological narrative of past events; it requires, as indicated by Husbands (2003), ‘… that we, history teachers … establish a more subtle, less absolutist understanding of the way in which knowledge is created … It needs to be developed through the process of inquiry in the classroom, by teachers and learners in classrooms working to create meanings’. In a similar way Tsaparlis (1997b, p. 924) has emphasised the historical method of teaching as a way of better understanding the topic of atomic and molecular structure.

Moreover, as indicated in the previous discussion of reduction, an issue such as this requires in its teaching, the recognition of the different philosophical positions that underlie its foundation (Karakostas and Hadzidaki 2005). About realism, and the reality of electrons, the influential philosopher I. Hacking has said (1983, p. 22): ‘If you can spray them, then they are real …’. Others, like Achinstein (2001), in discussing the discovery of the electron, put forward the following components for a discovery:

- Ontological—Discovering something requires the existence of what is discovered.
- Epistemic—A certain state of knowledge of the discoverer is required.
- Priority—Social recognition of the discovery.

In the same book Arabatzis (2001) offers a consensus-based account of discovery, asserting that entity x (atom, electron, spin and phlogiston) can be said to have been discovered just when a group y reaches consensus that it has been. He simply wishes to concentrate on synchronous belief, not on reality. However, in another chapter of the same book, Morrison addressed the reality of spin (2001). These discussions can be very technical and complicated. Nevertheless it is advisable for a teacher to adopt a position or at least to know it.

In recent years, for example, several authors have recognised that the way chemistry is usually taught is based on a particular philosophical position and that in general terms this position is logical positivism (Chamizo 2001; Erduran and Scerri 2002; Van Aalsvoort 2004; Van Berkel et al. 2000). Van Berkel with researchers all around the world analysed current and post-war textbooks and syllabi representative of secondary chemistry education in most Western countries trying to find why they are so remarkably similar. He recognises that dominant school chemistry is particularly isolated from everyday life and society, history and philosophy of science, technology and chemical research. His main conclusion was:

> The structure of the currently dominant school Chemistry curriculum is accurately described as a rigid combination of a substantive structure, based on corpuscular theory, a specific philosophical structure, educational positivism, and a specific pedagogical structure, initiatory and preparatory training of future chemists. (van Berkel 2005, p. 67)

During the Cold War, a philosophy of science, which defended science's superior analytical purity, was enthroned in most of the Anglo-Saxon intellectual world (Echeverria 2003). It focused on science methodology and the reduction of various scientific disciplines to physics. Since then, the best known version of logical positivism, presenting science as a linear succession of successful discoveries and placing the emphasis on factual recall with confirmatory experiments, has contributed to identifying what kinds of research questions and issues were adequate not only for axiomatic science (Reish 2005) but also for school syllabus, as can be seen in chemistry and physics curricula. Therefore it would be desirable, regardless of the educational level, when addressing the teaching of atomic and molecular structure, to identify the philosophical position underlying the approach.

Journals oriented to chemistry education are dedicating full sections to the history of chemistry. William B. Jensen, since 2003 until recently, had the responsibility of writing a section 'Ask the historian' in the *Journal of Chemical Education*. He previously had devised a framework of three chemical revolutions from which he extended three levels of comprehension of chemistry—Molar, Molecular and Electrical—and three dimensions, based on whether they deal with composition/structure, energy or time (Jensen 1998). In that set of articles, Jensen commented that there are a large number of histories of chemistry. In his bibliographic study, Jost Weyer (1974) listed no fewer than 71 general histories of chemistry written between 1561 and 1970, of which 29, or roughly 40 %, have appeared written in English. George B. Kauffman has the responsibility of writing historical articles for the journal *The Chemical Educator,* mainly to commemorate anniversaries of outstanding achievements in chemistry (some examples are Kauffman 1999, 2004, 2006, 2010). Jaime Wisniak has played a similar role in *Educación Química*, the Ibero-American Journal of Chemistry Education, since 2001 (Wisniak 2013).

However, although there are many scholarly works on the history of chemistry, there have been few on how to incorporate them, effectively and systematically, into the teaching of chemistry. Perspectives, such as that established by Jensen (1998), in which the curriculum is built on history (in this case of atoms and molecules), or that described by Early (2004) from a new philosophical basis, are few and therefore very important. As Talanquer recognised (2011) school chemistry needs transgression.

12.3.3 Introduction to Alternative Conceptions and Difficulties in Teaching and Learning Quantum Mechanics and Quantum Chemistry

Many studies have reported students' difficulties in grasping the fundamental issues of quantum mechanics and quantum chemistry in high school. We shall mention first an article by Tsaparlis and Papaphotis (2002) where findings of student difficulties with quantum numbers, atomic and molecular orbitals, are reviewed, and a case is presented against using quantum chemical concepts at this level (Bent 1984).

These authors insist that the topic is highly abstract and therefore beyond the reach of many students.

Students have difficulty understanding the concepts of atomic and molecular structure (Harrison and Treagust 1996) because of the abstract nature of the submicro world (Bucat and Mocerino 2009). Many authors have been discussing in several studies the difficulties or misconceptions in students' learning about matter—those related to its particulate nature,[3] to bonding in general,[4] to the covalent bonding model,[5] to the metallic bonding model[6] and to the ionic bonding model.[7]

Other studies have reported students' difficulties in grasping the fundamental issues of quantum mechanics and quantum chemistry at high school[8] and college levels.[9] In particular the following concepts are indicated:

- 'Probability and energy quantization' (Park and Light 2009)
- 'Quantum numbers' or 'electron configurations of chemical elements'[10]
- 'Orbital ideas'[11]
- 'Uncertainty and complementarity' (Pospiech 2000)
- 'The Schrödinger equation' (Tsaparlis 2001)

From the point of view of teaching, the elementary, qualitative and pictorial coverage of quantum chemical concepts is approached with reservation or with strong opposition by many chemical educators (Bent 1984; Gillespie 1991; Hawkes 1992).

Physicists have also recognised the difficulties involved in understanding quantum mechanics (Einstein 1926, 1944, 1948; Feynman 1985; Laloë 2001; Styer 2000).

Taber (2003) mentions 'most alternative conceptions in chemistry do not derive from the learner's unschooled experience of the world'. The many problems that learners have in chemistry maybe best characterised as 'model confusion' (see Sect. 12.3.4.4). Where there are several models for particular or closely related chemistry concepts, students become greatly confused. This is particularly so when most learners have a very limited notion of the role of models in science (Grosslight et al. 1991).

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[3] See, for example, Lee et al. (1993), Novick and Nussbaum (1978, 1981), Nussbaum (1985), Valanides (2000), and Wightman et al. (1987).

[4] As can be seen in Birk and Kurtz (1999), Boo (1998), Furió and Calatayud (1996), Griffiths and Preston (1992), Hund (1977), Kutzelnigg (1984), Magnasco (2004), Özmen (2004), and Sutcliffe (1996).

[5] For example, Coll and Treagust (2002), Niaz (2001), and Peterson et al. (1989).

[6] Such as in Coll and Treagust (2003a) and De Posada (1997, 1999).

[7] See, for example, Butts and Smith (1987), Coll and Treagust (2003b), and Taber (1994, 1997).

[8] Such as Dobson et al. (2000), Petri and Niedderer (1998), Shiland (1995, 1997), and Tsaparlis and Papaphotis (2002, 2009).

[9] For example, Hadzidaki et al. (2000), Johnston et al. (1998), Kalkanis et al. (2003), Michelini et al. (2000), Paoloni (1982), and Wittmann et al. (2002).

[10] As can be seen in Ardac (2002), Melrose and Scerri (1996), Niaz and Fernández (2008), and Scerri (1991).

[11] For example, Cervellati and Perugini (1981), Conceicao and Koscinski (2003), Ogilvie (1994), Scerri (2000a), Taber (2002a, b; 2005), and Tsaparlis (1997a).

12.3.4 Experiences

12.3.4.1 Similarities

This subject is closely related to the previous subsection. One of the first to establish similarities between the historical development of science and the conceptual development of students was J. Piaget (Piaget and Garcia 1983) followed by Gagliardi (1988), although Matthews (1992) identifies this idea in Hegel's *The Phenomenology of Mind*. There are strong grounds for criticism of this position (Gault 1991), mainly because the equivalence between the ideas of scientists and students has not been demonstrated. Nevertheless, Scheffel and colleagues (2009) recently and carefully used the similarities in classroom teaching through the following sequence:

1. The teacher hands on historical, but educational purposes reduced, material to the student. This will presumably pick up students' misconceptions and their actual scientific positions.
2. The students discuss these ideas and propose experiments to verify or falsify one of the theories or models that has been presented. They have an opportunity to choose one of the scientists as an advocate for their preconceptions.
3. Based on experiments and if necessary on additional material, the pros and cons of each theory or model are collected and discussed. If possible, a decision should be formulated and explained.

These authors provide examples of similarities, applying this teaching methodology to old atomism, chemical bonding or Lewis octet model.

12.3.4.2 The Historical Narrative

Narrative can be defined as 'telling someone else that something happened' (Herrestein-Smith 1981, p. 228). Norris and colleagues (2005) elaborated this approach, and they identified in the narrative the roles of the narrator, the reader and the events. Particularly important here is the responsibility of the narrator—in this situation, the teacher—because he or she must facilitate the interpretation of the events in context (Gilbert 2006). As Metz and colleagues (2007) recognised, the narrative approach has a spectrum of possible applications:

- Interactive vignettes (Wandersee and Griffard 2002)
- Anecdotes (Shrigley and Koballa 1989)
- Curriculum unit unified by a theme (Holbrow et al. 1995)
- Storyline, when the thematic approach will begin with a big question (Stinner and Williams 1998)

For example, Teichmann (2008) included anecdotes from some atomic structure protagonists; Klassen (2007) has used narratives for teaching the heroic attitude of L. Slotin assembling the first atomic bomb and for rehabilitating the story of the Photoelectric Effect (2008). In similar fashion, Nobel lectures have also been used for teaching in chemistry and in physics (Jensen et al. 2003; Panusch et al. 2008;

Stinner 2008). Biographies, tributes and interviews could also be considered in this category. Some examples are G. N. Lewis (Branch 1984), L. Pauling (Kauffman and Kauffman 1996) and R. S. Mulliken (Nachtrieb 1975).

12.3.4.3 The Historical Role of Rivalry, Controversy, Contradiction, Speculation and Dispute in Scientific Progress and Its Use in Teaching Strategies

In academia, conflicts in and around science have been studied for various reasons:

- To gain insight into the process of science policy making process
- To learn more about the various roles of scientists
- To identify the ways in which the public might participate in decision making
- To understand how controversies arise, how they are contained within the scientific community or expand into the public domain, how they are brought to a close or why they persist, among others
- To analyse the social construction and negotiation of scientific knowledge claims by conflicted scientists (Martin and Richards 1995)

Nevertheless, dispute in scientific progress has been rarely used in the teaching and learning of science (Niaz 2009).

Teaching through the consideration of historical aspects of scientific knowledge has the potential to show the progress of scientific knowledge over time. Historical artefacts and scientific discoveries, scientists' life stories and the details of scientific struggles in scientific progress could be discussed in the science classroom. Because the knowledge represented in textbooks or in any predesigned science-learning environment context is the end product of science, students and teachers do not learn and teach about those presuppositions, contradictions, controversies and speculations existent in scientific progress (Niaz 2009, 2010; Garritz 2012 online). Only a few teachers today believe and teach that scientific knowledge is tentative, empirically based, subjective and parsimonious; that it includes human creativity and imagination; and that it is socially and culturally constructed (Ayar and Yalvak 2010).

12.3.4.4 The Explicit Recognition of Models and Modelling

The Model-Based view of Scientific Theories and the structuring of school science (Adúriz-Bravo 2012; Develaki 2007) have recently been discussed elsewhere. As discussed earlier in this chapter, quantum mechanics forced physicists and chemists to reshape their ideas of reality, to rethink the nature of things at the deepest level and to revise their concepts of determinacy vs. indeterminacy, as well as their notions of cause and effect. Here we adopt a realist position about molecules, atoms and electrons. In agreement with Tapio (2007), we specify that:

- Reality and its entities are ontologically independent of observers.
- Claims about the existence of entities have truth-value.
- Models of atoms and molecules are required to be empirically reliable.

Model is a polysemous word; it has been used and it is still used with several meanings. That is one of the difficulties we meet when we use it in teaching. In one usage, ‘model’ is exemplary; it indicates things, attitudes or people worthy of emulation. The courage of a warrior, the intelligence of a wise man, the solidarity of a doctor and the speed of a runner are examples of ‘models’ in this regard. In this paper we use a previous definition of ‘model’ (see Chamizo 2011 for all the references): ‘models (m) are representations, usually based on analogies, which are built contextualizing certain portion of the world (M), with a specific goal’. In this definition all the words are important: the representations are essentially ideas, but not necessarily so, as they can also be material objects, phenomena or systems (all of them constitute a certain part of the world M). Representations have no meaning by themselves; they come from someone (either an individual or a group, usually the latter) that identifies them as such. An analogy is made up of those features or properties that we know are similar in (m) and (M). That ‘are built contextualizing certain portion of the world M’ refers to a historically defined time and place which also frames the representation. Some ‘portion of the world’ indicates its limited nature; models (m) are partial for the world (M). ‘A specific goal’ establishes its own purpose, usually (but not necessarily) to explain or teach and possibly also to predict. In this sense models can be understood as cognitive artefacts or mediators constructed in order to create subjective plausibility about the target. It is important to remember that explanation is one of the most significant features of science, but in some cases when models are even completely unable to offer an explanation, much of the prestige of a model may lie in its capacity to predict.

There are only two types of models: mental and material.

Mental models are reflected representations built by us to account for (explain, predict) a situation. They are forerunners of the famous ‘misconceptions’ (see Sect. 12.3.3) and can sometimes be equivalent, since they are unstable, generated in the moment and then discarded when no longer needed, making them cognitively disposable.

Material models (which may be identified as prototypes) are the ones that we have empirical access to and have been built to communicate with other individuals. Material models are expressed mental models and can be further categorised as symbolic, iconic or experimental. Here we only discuss the first two. Symbolic material models correspond to the languages of sciences, such as mathematics or chemistry. So mathematical equations constructed to describe precisely the portion of the world being modelled are symbolic material models. Wave mechanics is a symbolic material model. Another example of symbolic material model is the one used by chemists to represent elements, compounds and reactions. Hence, when a teacher writes the molecular structure of water as H_2O using two hydrogen and one oxygen atom, the teacher uses a symbolic material model. Iconic material models correspond to images, diagrams or scale models, like a map or the so-called molecular models. Stereochemistry was constructed with iconic material models in three dimensions. For example, in the early years of the nineteenth century, Dalton constructed wooden models of atoms; after him Pasteur made his models of enantiomer tartrate crystals, Hofmann his croquet ball molecular models and van’t Hoff his cardboard tetrahedral models. In the twentieth century the stereochemical ideas of Pauling led to the most famous example of an iconic material model, the DNA structure by Watson and Crick.

Recently Seok and Jin (2011) have reviewed the literature dealing with models and modelling and reported some important findings. Two of them related to model use in atomic and molecular structure teaching are:

- Meaning of a model. A model is understood as a representation of a target. The targets represented by models can be various entities, including objects, phenomena, processes, ideas and their systems. A model is also considered a bridge or mediator connecting a theory and a phenomenon, for it helps in developing a theory from data and mapping a theory onto the natural world, for example, atomic models (Dalton, Bohr, Lewis), molecular models or bonding models (ionic, covalent, coordinated and metallic) or electron models (corpuscle or wave like).
- Change in scientific models. There are two ways of testing a model in science: the empirical and conceptual assessments. An empirical assessment is a way of evaluating a model in terms of the fit between the model and the actual phenomenon. In a conceptual assessment, a model is evaluated according to how well it fits with other accepted models as well as with other types of knowledge.

The assessment of a model is conducted differently in experimental sciences, such as physics or chemistry, from in historical sciences, or others, such as earth science. For example, Bohr's atomic model is excellent at explaining hydrogen spectra, but useless for molecular structures; Lewis' atomic model is excellent in predicting simple organic structures, but useless in, for example, infrared spectra (about Lewis model in introductory teaching of atomic and molecular structure see Chamizo 2007; Purser 2001).

Finally because models are built in a particular historical moment for specific purposes, the context should be explicitly recognised when teaching them. Justi and Gilbert (2000) have warned us about the frequent use of hybrid models in the textbooks, which has produced so much confusion among students. Experiences of more correct use of these models have been reported recently (Chamizo 2007, 2011, 2012).

12.3.4.5 Textbooks, Experiments and Information and Communication Technologies (ICTs)

There are several books that feature various aspects of the history of atoms and molecular structure.[12] One of the most influential is Kuhn's *Black-Body Theory and the Quantum Discontinuity 1894–1912*. Another example is the history of quantum chemistry as told by E. Segrè (2007) in which a Nobel laureate offers impressions and recollections of the development of modern physics. Rather than a chronological approach, Segrè emphasises interesting, complex personalities who often appear only in footnotes. Readers will find that this book adds considerably to their understanding of science and includes compelling topics of current interest.

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[12] For example, Buchwald and Warwick (2001), Giunta (2010), Marinacci (1995), Nye (1993), Snow (1981), and Toulmin and Goodfield (1962).

However, very few of these last writers teach undergraduate chemistry. The authors of this chapter have written a book in Spanish on quantum chemistry, with emphasis on the development of the historical aspects of this science (Cruz et al. 1986). With hundreds of solved exercises and problems, it has been used widely in Ibero-America. The historical narrative oscillates in time, from the nineteenth-century chemistry until the interpretation of periodicity, as can be seen in Table 12.4.

Experiments related to the history of atomic and molecular structure are rare. Some of them can be found in more general books like Doyle's *Historical Science Experiments on File* (Doyle 1993). However, there are some examples, ranging from the electrochemical decomposition of water (Eggen et al. 2012) to spin through the Stern-Gerlach experiment (Didis and SakirErkoc 2009).

Information and Communication Technologies (ICTs) have so far had little impact in this area, with the exception of graphs of orbitals, electron densities and contours. The PhET project (Physics Education Technology) has branched also into chemistry and biology. Some of the designed computer simulations have been devoted to atomic and molecular structure from historical experiments. PhET conducts research on both the design and use of interactive simulations, but important as this material is, the failure to address historical context and provide historical references has made this approach so far quite weak.

12.4 Conclusion

Physical chemistry remains a fundamental basis for the teaching of chemistry. Mathematics, as group theory and matrix representations, is needed to understand selection rules via symmetry studies and, through them, spectroscopic transitions, an important topic since the second half of last century. Nevertheless there is a necessity for balance between the theoretical physicochemical basis of chemistry and the phenomenological and empiricist knowledge that chemistry had already produced.

The parsimonious advice of one of the reviewers of this chapter was 'do not introduce needless complexity unless it is warranted to explain the necessary facts'. This can be also a conclusion about the inclusion of history and philosophy of science in teaching quantum mechanics and quantum chemistry. One has to apply Ockham's Razor rules while teaching these topics.

We can recognise in the almost 200 works cited in this study that integration of history of science into the teaching of atomic and molecular structure has been seen as an important step, particularly since 1994. Increasing numbers and diversity of resources and studies of strategies to be used are making this incorporation more robust. Nevertheless, the way in which chemistry has been taught all around the world is based on a particular philosophical position, which comes from its acceptance as a reduced science, and can be characterised as logical positivism. This normal (in Kuhn's terminology) education practice has not been driven to any great extent by educational, historical or philosophical research findings. A few years ago J. Moore, as editor of the influential *Journal of Chemical Education* (2005),

Table 12.4 Some chapters of the book by Cruz et al. (1986)

Chapter	Comments
The chemistry of the nineteenth century	From Dalton atomic hypothesis to Couper and Kekulé molecular models through Frankland and Werner's valence models and finally to the Mendeleev's work, as the empirical foundation of periodicity
Birth of quantum theory	Thomson's corpuscles discovery in cathode ray tubes, the Millikan controversial experiment of determination of the electronic charge (Niaz 2000; Panusch et al. 2008; Paraskevopoulou and Koliopoulos 2011) and back to the black-body radiation experiments of Stefan, Wien, Lummer and Pringsheim, Rubens and Karlbaum that conducted M. Planck to the correct radiation formula and a couple of months later to the proposal of quantum theory as a brilliant solution to the ultraviolet catastrophe found theoretically by the classical analysis of Rayleigh and Jeans. This chapter closes with Einstein's light quantum hypothesis, his explanation of the photoelectric effect and finally with the Compton experiment that confirmed the photon existence
Atomic spectra	Bohr's atomic model of one electron atom as it was presented by him in 1913 and considering that Rydberg's formula is in itself a premise of his model. After the postulates of Bohr's model, the Sommerfeld and Wilson quantisation rules are depicted, and the elliptic orbits with three quantum numbers are introduced, with the angular momentum modified; the Frank and Hertz experiment, the fine structure of hydrogen spectrum and the Moseley law show the successful application of Bohr's model
Models of atoms and chemical bonds	The Lewis and Langmuir's model of covalent bond, Kossel's model for ionic bonding and also Pauling's electronegativity are followed by Born-Haber's cycle and Fajans' rules
Discovery of electronic spin	After the electron spin discovery is presented, spin dependent models of the atom and molecular structure, such as the Gillespie and Nyholm's Valence Shell Electron Pair Repulsion model and the Linnett double quartet model, are introduced
Modern quantum mechanics (three related chapters)	The two proposals of Schrödinger and Heisenberg, later shown to be equivalent, and their application to the mono-dimensional free particle, to the particle in a box, to the hydrogen atom and to polyatomic structure, including the philosophical interpretations of quantum mechanics (Copenhagen's, stochastic, Schrödinger's cat, Einstein-Podolsky-Rosen, etc.)
The periodic behaviour of the elements	Periodicity empirically discovered by Mendeleev is now explained. A clear distinction between isolated electronic properties such as ionisation energy and electron affinity and those which come from the chemical environment, such as atomic size and electronegativity

indicated the poor impact of chemical education research on teaching and learning, in spite of the motto of the National Association of Research in Science Teaching: 'Improving Science Teaching and Learning Through Research'.

There still has not been major change regarding what the teaching of sciences requires. In general, the majority of teachers, textbooks and science curricula still consider science teaching as a dogma or as 'rhetoric of conclusions' (Schwab 1962). This situation can only change if teachers know and recognise the uniqueness of chemistry and the philosophical positions from which they approach their practice. Realism and models are some of the issues involved. Some ideas from the historian of chemistry M. J. Nye could be very helpful:

> We can say that if mechanics has always been an aim of scientific philosophy, the twentieth-century chemistry has revived its philosophical character, achieving a long-sought understanding of the dynamics of matter. But chemists more that physicists, have remained self-conscious about the fit between the phenomena taking place in the laboratory and the symbols employed in the operations of explanatory mathematics. Precision, not rigor, has been characteristic of chemical methodology. Parallel representations, not single causal principle, have been characteristic of chemical explanation.
>
> Whereas many early-twentieth-century physicists were inclined to regard conventionalism, complementarity, and indeterminacy as concessions of failure in their traditional philosophical enterprise, chemists were not surprised that a simple, "logical" account of the behaviour of electrons and atoms, like that of molecules and people, often gives way to the inconsistencies and uncertainties of empiricism. (Nye 1993, p. 282)

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Part III
Pedagogical Studies: Biology

Chapter 13
History and Philosophy of Science and the Teaching of Evolution: Students' Conceptions and Explanations

Kostas Kampourakis and Ross H. Nehm

13.1 Introduction

This handbook is about the inclusion of the history and philosophy of science (hereafter HPS) in science education. For the past 30 years (at least), there has been lively discussion (and debate) about what HPS scholarship can contribute to science education and how important this contribution can be. This chapter provides examples of why HPS is of central importance to evolution education research and instruction. This and the following chapter not only argue for the centrality of HPS scholarship for evolution education. Rather, they argue that evolution education research and instruction are based on poor standards if they are not appropriately informed by relevant HPS scholarship. Several aspects of the evolution education literature illustrate this point.

This chapter begins with a review of current perspectives on students' preconceptions about evolution and illustrates that attempting to shoehorn students' explanations about evolutionary phenomena into categorizations emblematic of particular historical figures is misleading, if not mistaken. Unfortunately, teaching evolution in its historical context has often been based on questionable characterizations of history: first, that students initially hold "Lamarckian" preconceptions about evolution, and second, that the conceptual change process mirrors historical paradigm shifts from "Lamarckian" to "Darwinian" frameworks. Careful reading of the historical literature suggests that students' ideas should not be labeled as "Lamarckian"

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(or "Darwinian") because their explanations are fundamentally different from those of associated historical figures. In addition, the process of conceptual change is much more complex than a straightforward shift from "Lamarckian" to "Darwinian" perspectives. Indeed, the actual history of evolutionary thought does not reflect the clean replacement of one evolutionary "paradigm" with another. The history of science appears to conflict with science educators' conceptualizations of it.

A more fruitful role for HPS scholarship in evolution education may be to guide the development of theoretical frameworks for exploring the structure of students' explanations of evolutionary change (e.g., Kampourakis and Zogza 2008, 2009). Several accounts of explanation have been proposed in the philosophy of science, but few have been integrated into evolution education research or practice. Although much of this literature is too complex for most students, core aspects of it may be effectively utilized in the development of conceptual heuristics for explaining evolution. Specifically, students would benefit from awareness that explanations in general have a causal structure and that evolutionary explanations in particular also have a historical nature. Evolution in particular (and biology in general, see Brigandt 2013a) is characterized by explanatory pluralism. Students would also benefit from learning that different evolutionary concepts may be linked to different kinds of explanations. For example, natural selection is an important, but not the only important, explanatory principle in evolution. Adaptations may be explained by invoking natural selection, but homologies may be explained on the basis of common descent.

In addition to gaining an understanding of the diversity of explanatory approaches used in evolutionary biology—and associated concept/explanation alignment—students must also be exposed to a greater diversity of explanatory *tasks*. Many of the commonly used simple explanation-based assessments in the evolution education literature (e.g., Nehm et al. 2012) could be pedagogically enhanced if they were to be modified to encompass more diverse explanatory contrasts. In line with these ideas, this chapter ends with a discussion of how HPS scholarship may be used to develop frameworks and tasks that can be used for teaching about the structure and historical nature of evolutionary explanations. This aspect of evolution education is particularly important given forthcoming standards emphasizing practice-based tasks (e.g., explanation and argumentation).

13.2 Students' Preconceptions of Evolution and HPS: A Review of the Literature

The history of science (HOS) may be used to provide ideas for designing instruction aiming at conceptual change (e.g., Jensen and Finley 1996; Passmore and Stewart 2002). However, making use of this strategy requires a careful framing of HOS as well as an understanding that there are significant differences between conceptual change in science and individual conceptual development (Gauld 1991). Historiography is a particularly important consideration when using HOS in science education because science is always enacted in particular social and cultural contexts. Thus, in order to understand how science is done, one must go beyond a superficial reading of HOS and engage with the nuances of particular historical episodes, contexts, and social networks. This section reviews studies analyzing students' preconceptions about evolution and illustrates the importance of historiography. Science education research examining student conceptual change patterns is also reviewed, and it is noted that individual conceptual change is in some cases quite different from conceptual change in HOS. Much of the discussion will focus on the evolutionary ideas of Jean Baptiste Lamarck.

Jean Lamarck was one of many naturalists across Europe involved in the debate concerning the fixity of species (Corsi 2005). Perhaps his most important contribution to natural history was that he replaced a static picture of nature held by his forerunners with a dynamic one in which life as a whole was constantly in flux (Mayr 1982, p. 352), an idea that had strong support from his earlier geological studies (Corsi 2001, p. 163). Lamarck's ideas can be considered as precursors to modern evolutionary biology because his work was the first attempt to develop a theory in which all organisms developed from primitive ancestors (Bowler 2003, pp. 86–87). In fact, his theory can be considered as the first major evolutionary synthesis in modern biology (Corsi 2001, p. 11), which shaped the debates that ultimately led to Darwin's theory of evolutionary change.

Lamarck proposed a complex model of evolutionary change. It included spontaneous generation as the starting point for the lowest forms of life, progressive forces that carried life up to higher levels of organization, adaptation caused by changes in individual organisms through use or disuse, and the inheritance of acquired traits as changeable hereditary material could be transmitted to the next generation (Mayr 2002, p. 81). Lamarck was not a teleologist; he did not recognize any "guidance" of evolution towards a goal and accepted only mechanistic explanations for biotic change. Indeed, Lamarck's causal chain (connected by a complex process of nervous fluid dynamics) began with needs imposed by the environment, continued with efforts of physiological excitations, and ended with the stimulation of growth resulting in the alteration of biotic features (Mayr 1982, p. 357). Lamarck believed that animals' needs determined how they would use their body parts, and the effects of use and disuse would cause some parts to increase in size by attracting more of the nervous fluid, whereas disused organs would receive less fluid and would degenerate (Bowler 2003, p. 92). Lamarck thought that through this process species could change but could not become extinct; he considered natural extinction to be inconceivable (Burkhardt 1995, p. 131). Lamarck was also not a vitalist; his theory was materialistic and provided a mechanistic explanation for the power of life (Burkhardt 1995, p. 151).

Contrary to common wisdom, it was not Lamarck but Charles Darwin who in fact held that environmental changes, acting either on the reproductive organs or on the body, were necessary to generate variation. Darwin hypothesized that the body was made up of units that increased by self-division or proliferation and were ultimately converted into various body tissues. These units could throw off minute granules (gemmules) that could develop into units similar to those from which they

Table 13.1 The main points of difference between Lamarck's and Darwin's theories of evolution (Based on Kampourakis and Zogza 2007)

Concept	Lamarck	Darwin
Common ancestry	Denied: spontaneous generation of life was occurring all time	Accepted: evolution had a branching form from common ancestors
Variations	Unfortunate consequences of imperfection in the process	Indispensable precondition of continuing evolutionary change
Species	Species did not exist but were convenient fiction	Species existed precisely because of naturally occurring variations
Unit that evolves	The overall process of evolution was modeled on the development of individual organisms and evolution was driven by changes in individuals	Populations evolved and developmental ontogeny explained individual characteristics, while selection explained the characteristics of the population and hence phylogeny
Mechanism of evolution	Transformation of individuals: progress of individuals from simpler to more complex forms	Natural selection in populations: differential survival in populations based on existent variation in a particular environment
Extinction	Denied: nature was powerful enough to ensure that no form could ever completely die out	Accepted as an important feature of the mechanism of natural selection

were originally derived (Winther 2000). In Darwin's model, variability resulted from changed conditions during successive generations. Either gemmules aggregated in an irregular manner, causing modifications in the offspring, or certain parts of the body could throw off modified gemmules that would give rise to similarly modified structures in the offspring. Under the right conditions, modified gemmules would continue multiplying until they replaced the old, unmodified ones and the offspring might gradually vary further through successive generations.

Darwin also believed that the inheritance of acquired characters was possible. However, in scientific studies during Darwin's time, it was observed that a removed part or organ in a parent could reappear in its offspring. Such findings contradicted Darwin's hypothesis, but he dealt with such findings by arguing that gemmules derived from reduced or useless parts would be more liable to diminish in size than those derived from parts which were still functionally active (Winther 2000; Endersby 2009; for the wider context, see Kampourakis 2013a). The main features of Darwin's and Lamarck's theories are presented in Table 13.1. It is important to be aware of these features in order to determine whether students' ideas/explanations bear any resemblance to Darwin's and Lamarck's theories of evolutionary change.

Researchers in science education have often noted similarities between ideas in HOS and students' ideas. For example, in many research articles, students' preconceptions about evolution have been characterized as "Lamarckian." However, it seems that not all researchers use the term *Lamarckian* in the same

Table 13.2 Ideas described by the term "Lamarckian" in the literature (*E* explicitly stated, *I*: could be implied). Studies published after 2007 that explicitly agree with the conclusions of Kampourakis and Zogza (2007) are not included in this table (Based on Kampourakis and Zogza 2007, revised and updated)

	Lamarckian idea		Non-Lamarckian idea	
Reference	1. Change due to use and disuse of body parts	2. Change due to inheritance of acquired traits	3. Change due to a predetermined final end	4. Change imposed by need
Pazza et al. (2010)		**E**		
Battisti et al. (2010)	**E**	**E**		**I**
Berti et al. (2010)	**E**		**E**	
Geraedts and Boersma (2006)	**I**	**E**		
Banet and Ayuso (2003)		**E**		**E**
Alters and Nelson (2002)	**E**	**I**	**E**	**E**
Passmore and Stewart (2002)	**E**	**E**	**E**	**E**
Samarapungavan and Wiers (1997)	**E**		**E**	**E**
Jensen and Finley (1996)	**E**	**E**		
Demastes et al. (1996)	**E**	**I**		
Settlage (1994)	**E**	**I**		
Jiménez-Aleixandre (1992)	**I**	**E**		
Bishop and Anderson (1990)	**I**	**E**		
Clough and Wood-Robinson (1985)			**E**	**E**
Brumby (1979)				**E**
Deadman and Kelly (1978)	**E**	**I**		

sense, and the term does not always accurately mirror Lamarck's ideas (see above and Table 13.1). Consequently, the meaning of the term *Lamarckian* is different among studies in the science education literature (see Table 13.2); in many cases Lamarck's two central concepts (change through use and disuse and the inheritance of acquired traits) are associated with two others which are *not* Lamarckian (Table 13.2, right columns) and imply a teleological process of change (to achieve a predetermined end or to satisfy needs).

As a result, two major problems arise: (1) different ideas are implied by the term *Lamarckian,* misrepresenting the actual content of students' preconceptions about evolution and (2) Lamarck's actual contributions to the history of evolutionary thought are also misrepresented. Thus, readers who are familiar with the history of evolution may understand *Lamarckian* to only refer to change through "use or disuse" or "inheritance of acquired traits" and ignore students' teleological explanations. On the other hand, the reader who ignores the historical facts might arrive at the conclusion that Lamarck's views and students' preconceptions are equally and similarly inaccurate (for details see Kampourakis and Zogza 2007). Thus, a proper understanding of HOS is of considerable importance to evolution education research.

Many researchers have begun to acknowledge the frequent mischaracterization of Lamarck's ideas in science education scholarship.[1] Nevertheless, some researchers not only continue to overlook this research but also continue to embrace a mistaken understanding of what HOS may contribute to science education. We believe that it is problematic to describe students' preconceptions as "Lamarckian" (or "Cuvierian," or "Paleyian," or "Darwinian") because in all cases it is problematic to compare students' conceptions (mostly naïve in the psychological sense) with the conceptual schemes proposed by important thinkers of the past. Lamarck, Paley, and Cuvier, for example, each possessed very detailed understandings of organisms' structures and physiologies and proposed equally detailed (although occasionally quite speculative) explanations (e.g., for the origin of adaptations). The same situation is almost never the case with secondary students or most undergraduates.

For instance, when comparing student ideas to those of Lamarck, Prinou and colleagues (2011, p. 276) note: "…conceptions of the pupils are called *Lamarckian* because 'the capacity of organisms to react to special conditions in the environment' (which does not occur directly but by a chain of events/complex mechanisms which Lamarck describes in his work) was considered by Lamarck as the second cause of evolutionary change." This quote raises the question as to whether students ever provide a description of the chain of events or complex mechanisms that Lamarck describes in his work (see above). Prinou et al. do not provide any evidence for such complexity. Instead, they describe students' preconceptions as *Lamarckian* because "organisms can develop new adaptive characteristics in response to environmental demands -which is a Lamarckian principle" (quoting Samarapungavan and Wiers 1997).[2] Prinou et al. (2011, p. 276) also note: "This goal-directed (teleological) reasoning noted in the pupils' explanations regarding the origin of biological adaptations, proves to be the predominant one used by pupils of various ages."[3] Teleology was not a central feature of Lamarck's evolutionary model.

Other authors also appear to have misunderstandings about Lamarck's ideas. For instance, although Berti and colleagues (2010) correctly recognize that Lamarckian preconceptions are not widespread, they write: "Only two children

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[1] See, for example, Kampourakis and Zogza (2007), Gregory (2008, 2009), Evans (2008), Evans et al. (2010), Bizzo and El-Hani (2009), van Dijk (2009), van Dijk and Reydon (2010), Smith (2010), Tavares et al. (2010), González Galli and Meinardi (2011), and Zabel and Gropengiesser (2011).

[2] But this principle could, in the same superficial manner, be attributed to Darwin as well (see Nehm and Ha 2011).

[3] This is exactly the conclusion drawn by Kampourakis and Zogza (2007); most students hold teleological conceptions, although some students may also have conceptions similar to Lamarck's.

[…] showed a coherent synthesis, according to which God created the first animals and then made them evolve. This view corresponds to a theistic form of evolutionary account, like the view proposed by Lamarck and embraced by most Western religions" (p. 527). Attributing a theistic view of evolution to Lamarck is entirely mistaken; Georges Cuvier, for example, had criticized Lamarck's theory for being entirely materialistic (Bowler 2003, pp. 93–94).

Some authors improperly attribute ideas of intentionality to Lamarck. For example, Battisti and colleagues (2010) write: "In item 19, students of lowest LOUs are most likely to select the Lamarckian [sic] explanation that the lizards adapt because they 'want' to adapt" (p. 864). However, Lamarck did not attribute evolutionary changes to the willing of animals (i.e., intentionality). Lamarck referred to *needs* but did not think that an animal could develop a new organ by willpower alone. According to Mayr, this misunderstanding was caused in part by the mistranslation of the word *besoin* into "want" instead of "need" (Mayr 1982, p. 357).

To summarize, the evolution education literature contains many historical errors as well as cases in which students' preconceptions are inappropriately linked to historical figures (particularly Lamarck). Moreover, scientists like Lamarck and Darwin developed remarkably complex models of evolutionary change built on a deep knowledge of natural history; consequently, it is questionable as to whether terms like "Lamarckian" would ever be appropriate descriptions of students' mental models of evolutionary change. But even if they were, such a term would not be very informative because there are also substantial differences between conceptual change in the history of evolutionary thought and evolution education. This is the topic that we turn to in the next section.

13.3 The History of Evolutionary Ideas and Students' Conceptual Development

Historical overviews of the development of evolutionary thought have been considered by some science educators to promote understanding of evolution. One approach has been to have students become involved in activities that require them to compare and contrast alternative evolutionary models proposed throughout the history of science. For example, Jensen and Finley (1996, 1997) used this approach in an introductory university-level biology class. The first step in their study was the identification of students' preconceptions about evolution. Subsequently, four alternative evolutionary models drawn from the history of science were presented to the students (specifically, Cuvier's, Lamarck's, Paley's, and Darwin's models), and students were involved in a series of instructional activities relating to these models. The goal of this approach was to have students practice *using* alternative models to solve problems and to assess the relative merits of these models. The main conclusion from Jensen and Finley's studies was that students might generally increase their use of Darwinian concepts, but it was nevertheless more difficult to reduce their application of non-Darwinian concepts.

A similar approach to Jensen and Finley's studies of undergraduates was developed for high school students (Passmore and Stewart 2002; Passmore et al. 2005). Passmore and colleagues' studies were based on the presentation of the conceptual structure of three models developed to explain species diversity (Darwin's, Lamarck's, and Paley's models). Students were asked to compare the three models and assess their explanatory power by using them to explain phenomena different from those described in the original writings of these historical figures. It was hoped that these pedagogical activities would help students distinguish between those concepts that are components of the model of natural selection and those that are not. The goal of this approach was to engage students in inquiry activities that required them to use Darwin's model of natural selection in order to develop a narrative explanation. The main conclusion from these studies was that students could develop a rich understanding of natural selection and use that understanding to reason about evolutionary phenomena.

These studies suggest that involving students in activities that require them to construct and evaluate explanations using alternative evolutionary models has pedagogical value and may facilitate understanding of natural selection. However, there are complications with such HOS-based approaches. It should be made explicit to students that the different historical conceptualizations (e.g., Paley's, Lamarck's, Darwin's) were not discrete, contemporaneous alternatives; rather, Paley's and Lamarck's theories had an important influence on the development of Darwin's theory. While a student at Cambridge, Darwin initially accepted Paley's assumption that body structures existed because they were useful to organisms and reflected God's wisdom and design. But Darwin soon started thinking of adaptation in a different way, as a process by which species responded to environmental changes (Bowler 2003, p. 149). In contrast, Lamarck had suggested that the environment and its changes came first and made organisms use or disuse certain body parts and this eventually caused "adaptive" variations. While Darwin generally denied this view and thought of variation as already present in populations and induced by the environment, Lamarck's concept of local adaptation nevertheless became a central idea in Darwin's mechanism for evolution (Gould 2002, p. 175). Thus, in contrast to the pedagogical activities outlined above, HOS indicates that aspects of Paley's and Lamarck's theories had a significant impact on the development of Darwin's theory and facets of them became integrated into Darwin's model of evolutionary change. All too often, the conceptual and historical contrasts introduced in evolution education do not clearly reflect the growth of evolutionary thought.

The complex mixing of evolutionary ideas in the history of science also raises questions about whether discrete "paradigm shifts," a concept introduced by Thomas Kuhn, have characterized evolutionary thought. He argued that scientific advancement was characterized by a series of periods of "normal science" punctuated by intellectually violent revolutions in which particular conceptual worldviews were replaced. To describe these conceptual worldviews, Kuhn coined the term paradigm, which did not simply refer to the current theory, but to the entire worldview in which the theory was situated. According to Kuhn, scientific revolutions occurred when anomalies emerged which could not be explained by the accepted paradigm, which was eventually replaced by a new one. The change from an old paradigm to a new one was described as a "paradigm shift" (Kuhn 1996). It has been suggested that there are analogous (but not entirely similar) patterns of conceptual change in science learning—this is the classical perspective on conceptual change (Posner et al. 1982; but see Levine 2000; Greiffenhagen and Sherman 2008; Van Dijk and Reydon 2010; Vosniadou 2012).

Building on HOS and conceptual change research, it has been suggested that there is a striking similarity between the supposed paradigm shift from "Lamarckian" to "Darwinian" worldviews during the nineteenth century and students' conceptual change from "Lamarckian" to "Darwinian" perspectives (e.g., Jensen and Finley 1996). However, this view is not without complications. First, it is debatable as to whether a paradigm shift from a "Lamarckian" to a "Darwinian" perspective ever took place in the history of science. The history of the study of evolution before Darwin not only includes Lamarck but a much wider intellectual community in Europe that discussed the stability of species and produced many different views on the subject (Corsi 2005). The European scientific scene from the late eighteenth century to the mid-nineteenth century was complex, and debates about the transformation of species had already occurred around 1800. This milieu extended beyond naturalists in England and France (e.g., Erasmus Darwin and Étienne Geoffroy Saint-Hilaire) to Italian geologists and botanists, German naturalists and anatomists, and Russian paleontologists and zoologists (Corsi 2005). In sum, it is difficult to argue that there was just one prevailing pre-Darwinian perspective (e.g., a "Lamarckian" one) at any point in history.

Another complication is that there was no discrete *replacement* of an old evolutionary paradigm with a new one after the publication of the *Origin of Species* by Darwin (1859). As Darwin scholars Hodge and Radick have noted: "… to say that Darwin's influence has been more than revolutionary […] is just to say that there is no one transition that can be identified as the shift that replaced a pre-Darwinian with a Darwinian regime in Western thought" (Hodge and Radick 2009, pp. 267–268). Since it was first proposed, the idea of natural selection had to compete with many alternative models until the evolutionary synthesis of the 1940s took place (Bowler 1983). Indeed, there was no smooth transition from non-evolutionary views to an evolutionary perspective. Several of Darwin's supporters considered evolution to be a progressive and purposeful process. In addition, morphologists, paleontologists, and naturalists attempted the reconstruction of phylogenies, from which support for non-Darwinian mechanisms (such as neo-Lamarckism, orthogenesis, and saltationism) emerged. These ideas led to a rejection of the importance of natural selection, emphasized function and adaptation, and highlighted mechanisms connected to structural constraints on development and evolution (Bowler 2005). This explains, in part, why the reception of Darwin's ideas differed dramatically in different nations (see Engels and Glick 2008). Darwin's own theory was also, in some respects, quite different from the Darwinian theory of the first half of the twentieth century (Depew 2013).

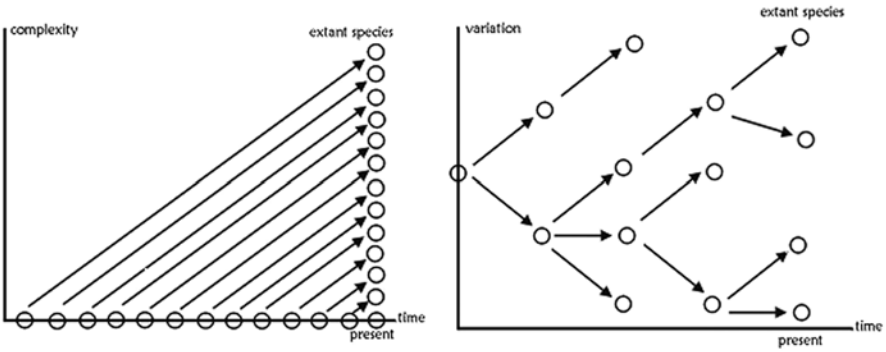

Fig. 13.1 Representation of the main features of Lamarck's (*left*) and Darwin's (*right*) theories (see also Table 13.1)

In addition to questions about whether HOS displays genuine paradigm shifts in evolutionary thought, it is also highly debatable as to whether student thinking shifts from a *Lamarckian* (or Cuvierian or Paleyian) paradigm to a *Darwinian* paradigm. For example, in one study, students were found to confuse Darwin's and Lamarck's theories as parts of the *same* explanation, and not as incompatible models (Jiménez-Aleixandre 1992). This produced inconsistencies in students' responses; they used one idea in one problem context and another idea in the same problem set in a different context (Jiménez-Aleixandre 1992). Many other studies have shown that substantial numbers of students have mixtures of Darwinian ideas (e.g., differential survival) and Lamarckian ideas (inheritance of acquired traits) before and after instruction (e.g., Nehm and Reilly 2007; Nehm and Ha 2011), raising the question as to whether students ever have coherent Lamarckian or Darwinian models (Kampourakis and Zogza 2009).

Two main differences worth noting between Darwin's and Lamarck's theories are the concepts of common descent and natural selection, which are central in the former and are absent in the latter (see Fig. 13.1 for an illustration). Since common descent and natural selection are central concepts of Darwin's theory, students are often taught them and instructed to apply them to explain episodes of evolutionary change. But it is inaccurate to describe students' preconceptions as "Lamarckian" just because they do not use common descent or natural selection to explain evolution. Moreover, in many cases, understanding natural selection requires understanding the mechanisms of heredity and of the origin of genetic variation through mutations (e.g., Banet and Ayuso 2003).[4] Given that the modern notions of heredity and mutation were unknown to Darwin, it is also inaccurate to describe the reasoning models that students display after instruction as *Darwinian* because such understanding differs

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[4] Teaching genetics before evolution seems to facilitate understanding of evolution by secondary students (Kampourakis and Zogza 2009; see Kampourakis 2006 for how genetics and evolution concepts can be connected).

from Darwin's own understanding. For these reasons, it seems inappropriate to describe the conceptual change process in evolution education as a shift from Lamarckian to Darwinian views.

Even when it is argued that students' explanations are similar in many respects to those of past scientists, important differences may also exist. Conceptual development in children may be less revolutionary than what actually occurs in science (Thagard 1992, p. 263). Thus, despite the interesting similarities between students' conceptions and early evolutionary ideas, there are important differences between individual conceptual development and the growth of evolutionary thought (Rudolph and Stewart 1998). The use of any labels originating from the history of science (e.g., Lamarckian, Darwinian) does not assist science educators in their attempts to develop a richer understanding of students' preconceptions. Despite similarities, two striking differences exist between the ideas of historical figures and students' preconceptions: (1) the intuitive development of students' ideas is a different process from the conscious theory construction of a scientist; and (2) students' conceptions are developed privately and are based on everyday experience, whereas scientists' ideas must be developed in consultation and confrontation with the views of other scientists and are usually based on preexisting scientific knowledge (Gauld 1991). In sum, many conceptual complexities confront science educators' attempts to draw parallels between scientists' explanations of evolutionary change and students' explanations of evolutionary change. What is important to emphasize is that students must learn to construct evolutionary explanations and this might be achieved by using sophisticated instruction informed by HPS scholarship. This is the topic of the next section.

13.4 HPS and Teaching About Evolutionary Explanations

Effective science instruction requires an appropriate presentation of key ideas and theories. In addition, effective instruction must support students in learning how to engage in scientific practices such as constructing explanations and arguments (NRC 2012). Given the increasing importance of the practice of explanation in science education research and standards documents (NRC 2012; McNeill and Krajcik 2008; Nehm et al. 2009), and its central role in evolutionary biology, we explore the topic of scientific explanation at some length.

Several accounts of scientific explanation have been proposed in the philosophy of science. In general, an explanation consists of an *explanandum* (whatever is being explained) and an *explanans* (whatever is doing the explaining). For example, if one asks "why X?" and the answer is "because Y," then X is the explanandum and Y is the explanans. It has been suggested that to explain something in science is (a) to show how it is derived in a logical argument that includes a law in its premise (the covering law model: Hempel and Oppenheim 1948), (b) to provide information about how something was caused (a causal account: Scriven 1959; Salmon 1984; Lewis 1986), or (c) to connect a diverse set of facts by subsuming them under some basic patterns and principles (the unification account: Friedman 1974; Kitcher 1981). It seems that there is general agreement among philosophers that the concept of *cause* is central to the process of scientific explanation.[5]

When trying to explain the causes of the presence of a particular biological trait, one may ask two different types of questions: (a) why it exists ("Why?" questions) and (b) how it functions ("How?" questions). Ernst Mayr (1961) is one of the first scholars to highlight this distinction. He divided the life sciences into *functional biology* (studies of proximate causes and answers to "How?" questions) and *evolutionary biology* (studies of ultimate causes and answers to "Why?" questions). In general, ultimate causes are related to the evolutionary history of species, whereas proximate causes are related to the function and physiology of individuals. Mayr's conceptualization of proximate and ultimate causes has been considered to be a major contribution to the philosophy of biology (Beatty 1994).

In recent years, Mayr's distinction has been reconstructed to include a broader conception of development (e.g., causal interactions between genes, extracellular mechanisms, and environmental conditions, rather than just the "decoding" of a genetic program) and a broader conception of evolutionary causes (e.g., natural selection, migration, and drift rather than natural selection alone). In this perspective, two distinct kinds of explanations exist: (a) proximate explanations, which are dynamic explanations for individual-level causal events and (b) evolutionary explanations, which are statistical explanations that refer to population-level events (Ariew 2003). However, given recent developments in evolutionary developmental biology, some scholars no longer consider this distinction to be valid due to the evolution of developmental processes and to how changes in these processes affect evolution (e.g., Laland et al. 2011). Nevertheless, the ultimate/proximate distinction retains an important pedagogical value (Kampourakis and Zogza 2008, 2009).[6]

Evolutionary explanations typically include the identification of past events that have a causal connection with the present (Scriven 1959, 1969). It is not possible to identify all of the causes of an evolutionary event; however, the causes of an event may at times be identified after it took place. As Cleland (2002, 2011) has noted, effects are underdetermined by causes, and causes are overdetermined by their effects. Simply put, this means that a single cause may not be adequate to bring about an effect (effects are underdetermined by their causes), whereas a

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[5] See, for example, Kitcher (1989), Salmon (1990), Okasha (2002, p. 49), Godfrey-Smith (2003, pp. 196–197), Woodward (2003), and Rosenberg (2005, p. 27).

[6] The ultimate/proximate distinction as described in these studies could be actually used to teach students about the distinction between developmental and evolutionary explanations. Research in evolutionary developmental biology (evo devo) suggests that such a distinction is not valid and that evolutionary and developmental processes constantly interact. Thus, an interdisciplinary approach to the study of these phenomena is required (Love 2013). However, especially in secondary educational settings, it may be important to first help students distinguish between development and evolution, especially since they often confuse the two kinds of processes. Having understood what development and evolution are, they could then be taught about how developmental changes have an impact on evolution as well as how developmental processes themselves evolve (Love 2013; Arthur 2004; Minelli 2009).

single effect can be an adequate indicator of its cause (causes are overdetermined by their effects). For example, a ball thrown at a window at low speed may not break it; however, observing a ball among fragments of glass on the floor could comprise adequate evidence for concluding that a ball was forcefully thrown at the window. Thus, evolutionary explanations are causal explanations with a historical dimension. They require phenomena or events which occurred in the past and which have a special causal relation with the effect observed (Scriven 1959). In other words, evolutionary explanations exhibit historical elements because they focus on properties that are unique in time and place and about which historical statements can be made (Lewontin 1969). Evolutionary explanations can thus take the form of historical narratives, and in such frameworks antecedent conditions play an important role. Explanations for particular evolutionary outcomes explicitly link them to particular antecedent conditions that have an explanatory role: if such conditions had been different, the outcome might have been different, too. The reliability of such explanations can be high as long as adequate information is available that causally links these antecedent conditions with the observed outcome (Gould 2002, pp. 1333–1334).[7]

Evolutionary explanations make extensive use of natural selection; however, a controversy emerges when one looks in more detail at what natural selection actually "explains." For some scientists, natural selection has a positive role and may help to explain why individuals have the traits they do, whereas for others it has a negative role in that it only eliminates variants and cannot explain why an individual has particular traits (see also Depew 2013). However, if one accepts that individuals belong to a lineage with a particular evolutionary history, then that history may help explain why they have particular traits (Forber 2005). Gould and Lewontin (1979) famously argued against the dominance of natural selection in evolutionary explanations by advancing the view that it is one of several important evolutionary processes. Other concepts—such as common descent and random drift—can (and often do) have explanatory roles (individually or collectively; see Beggrow and Nehm 2012). Indeed, Darwin's arguments in the *Origin of Species* included two central ideas: the tree of life (which involved two different ideas: transmutation and common descent) and natural selection (Waters 2009). That is why he described his theory as *descent with modification*.

Another important philosophical perspective on the historical nature of evolutionary explanations is the distinction between "how-possibly" and "how-actually" explanations. This type of explanation can be divided into: (1) *global how-possibly explanations,* which answer the question if some process could have produced evolutionary changes in an idealized population; (2) *local how-possibly explanations,* which answer the question if some process could have produced an observed evolutionary outcome or pattern consistent with what is known about an actual population; and (3) *how actually* explanations which answer the question why a

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[7] Interestingly enough Gould noted that such a kind of narrative explanation was central in Darwin's theorizing but his successors did not put emphasis on it in an attempt to base explanations on laws, which were considered more important for explanations than any narrative (Gould 2002, p. 1336).

particular evolutionary outcome or pattern occurred (Brandon 1990 pp. 176–184, and more recently, Forber 2010).[8]

In the science classroom, it is important to explain to students how it is possible to have epistemic access to the past (Cleland 2002, 2011; Forber and Griffith 2011). Students could be taught to develop "how-possibly" evolutionary explanations, test them against the available evidence, and then try to come up with "how-actually" explanations. Engaging in "how-possibly" and "how-actually" distinctions may be thought of as involving two distinct steps: (1) identification of antecedent conditions of the past which are causally related to the evolutionary outcome (effect) which is explained and (2) the identification of factors which were crucial in causing that particular outcome. The latter is based on the idea of "difference maker" factors, previously proposed in the literature on explanations (Lombrozo and Carey 2006; Strevens 2009). The important idea in this account is that there may be several causes of a particular phenomenon but one of them may be more important because it made "the difference" in eventually producing a particular outcome (but not another).

An example may help to illustrate this point. Suppose that a forest fire is observed. While the presence of both oxygen and a lighted cigarette may be causally connected to the forest fire, it is the latter that made the difference; that is, the cigarette is causally more important and thus has a more significant role in the explanation of the forest fire. The explanation of the forest fire takes the form of a historical explanation because one needs to explain how it actually started. In doing so, one may consider several "how-possibly" explanations, evaluate the available evidence, and then come up with a "how-actually" explanation. To take our example of the forest fire further, given that oxygen is always present in a forest, one could come up with the following two "how-possibly" explanations: (1) that lightning started the fire, due to the presence of oxygen and combustible material such as wood, and the fire then spread to the forest or (2) that humans lit a fire, which then spread to the forest due to the presence of oxygen and combustible material such as wood. One might then examine additional evidence from the past about the forest fire. If one finds that during the day that the fire started, there were no storms or lightning, but people were observed smoking cigarettes close to where the fire was observed, then one may conclude that explanation (2) is a more plausible "how-actually" explanation.

A biological example may also help to illustrate the distinctions between a "how-possibly" and a "how-actually" explanation. Possible causes of the presence of a long neck in a species of giraffe will be considered. There can be two kinds of causes, contemporary and historical ones. Contemporary causes may include (1) particular genetic/developmental mechanisms that causally affect the length of the neck in each individual and (2) some advantageous effect that contributed to its selection.[9] Assuming that a long neck is an adaptation and thus an outcome of natural selection

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[8] There is some disagreement in the details (Reydon 2012; Forber 2012) but the nuances of these disagreements are not central to our point.

[9] It is not necessary that the feature is currently being selected, but it may be so.

(see Kampourakis 2013b for suggestions about how to define adaptation in science education), historical causes should refer to the antecedent conditions that resulted in the evolutionary process that followed. In this case, giraffes with longer necks underwent selection for many generations in a particular environment in which a longer (than average) neck was advantageous and a shorter (than average) neck was disadvantageous; eventually the average neck length in the particular giraffe population increased over several generations. The antecedent conditions could have included the following factors with causal influence: (1) particular genetic/developmental mechanisms that causally affect the length of the neck in each individual, producing giraffes with a variety of neck lengths, and (2) particular environmental conditions (e.g., a drought that had limited the food supply) that caused natural selection. Of these two causes, (2) is the "difference maker."

It is important to emphasize that a different environmental condition could produce a different outcome: selection of shorter necks and eventually producing a shortening of neck lengths in the population or species. The fact that a condition can lead to different outcomes helps to identify it as a "difference maker." The everyday and biological examples that we presented are emblematic of the type of "how-possibly" explanations that students could be taught to construct. Then they might test alternative explanations against the available evidence (e.g., Mitchell and Skinner 2003).

In addition to gaining an understanding of the different explanatory approaches that are applied in the field of evolutionary biology, students must be exposed to particular *types* of explanatory tasks. For example, if students were asked to explain why birds have wings, they might answer that they have wings "in order to fly." This is an intuitive explanation that many children, adolescents, and adults would utilize. But if the explanatory task were framed in a slightly different way, and students were asked a slightly different question about birds and wings (e.g., How would a biologist explain why eagles, penguins, and ostriches have wings?), a conceptual conflict situation would immediately arise because the student would realize that his/her intuitive explanation (*in order to fly*) would be insufficient to explain why birds that do not fly (penguins and ostriches) have wings.[10] Thus, the structure of the explanatory task is likely to control the degree to which conceptual conflict and conceptual change occurs. Careful alignment of explanatory task types with instructional goals (e.g., formative assessment vs. conceptual conflict) has been lacking. The development of wider arrays of explanatory prompts for classroom use would be a useful pursuit.

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[10] It is entirely legitimate to say that *birds have wings for flying*, as long as we refer to birds which do use their wings to fly and if it is clear that it is selection and not design which is doing the explaining. In terms of their structure, evolutionary explanations are teleological explanations (Lennox and Kampourakis 2013). The problem for evolution education is not teleology per se, but teleology based on design (we do not discuss Intelligent Design in this chapter; an excellent, recent analysis can be found in Brigandt 2013b). This is a difficult topic, pedagogically speaking. Although reference to history may not be necessary for philosophical analyses, it can be very useful for evolution instruction (Kampourakis 2013b).

An important question to ask is how these perspectives on evolutionary explanations have been employed in the field of science education. Although scientific explanations have been the focus of increasing attention in educational standards documents (NRC 2012) and highlighted as central epistemic practices in science classrooms (Berland and McNeill 2012), less attention has been paid to the diverse ways that explanations have been conceptualized (see above) or how they should be appropriately taught, learned, and assessed. Indeed, for more than 30 years, while science education researchers have employed explanation tasks to reveal student thinking about evolution and natural selection (reviewed in Nehm and Ha 2011), they have paid comparatively less attention to the question of what most appropriately constitutes an "evolutionary explanation," and remarkably different epistemic perspectives have characterized evolutionary "explanations" in the science education literature.

For example, Gotwals and Songer (2010, p. 263), in a study of student thinking about biodiversity and evolution, conceptualized explanation "… as a response to a scientific question that takes the form of a rhetorical argument and consists of three main parts: a claim (a statement that establishes the proposed answer to the question), evidence (data or observations that support the claim), and reasoning (the scientific principle that links the data to the claim and makes visible the reason why the evidence supports the claim)." Conceptually similar to Gotwals and Songer (2010), Sandoval and Millwood (2005) linked aspects of argumentation to explanation: "Explanations are a central artifact of science, and their construction and evaluation entail core scientific practices of argumentation" (2005, p. 24). Sandoval and Millwood (2005) empirically studied "… the quality of the arguments that students make in explanations of problems of natural selection." Other authors have advocated for the linkage of explanation and argumentation in scientific explanations as well (McNeill and Krajciak 2008).

In contrast to Gotwals and Songer (2010), and Sandoval and Millwood (2005), Nehm and colleagues have excluded aspects of argumentation from their evolution explanation tasks. Rather, they have framed their explanation tasks as opportunities for students to build and apply causal accounts that explain differences between an initial biotic state and a subsequent biotic state (e.g., a cactus species with spines and a cactus species without spines; Nehm et al. 2012; Opfer et al. 2012). Nehm and colleagues' work nevertheless has never fully described what a normative evolutionary explanation should encompass (or should not), other than to note that it should include normative causal factors (e.g., mutation, differential survival, and heredity) and exclude nonnormative, noncausal factors (e.g., teleology, intentionality, inheritance of acquired characters). As these selected examples illustrate, quite different perspectives on evolutionary explanation have been put forth in the science education literature.

One recent study attempted to integrate HPS perspectives on explanation with pedagogical issues relating to the teaching and learning of evolution (Kampourakis and Zogza 2009). The aims of this study were (1) to teach students about the structure of evolutionary explanations and (2) to provide a conceptual heuristic applicable to different types of organismal features (i.e., homologies and adaptations). Students were taught to construct explanations for homologies by referring to a common ancestor that possessed the features that were common to the taxa discussed in the tasks. The general form of explanation they were given for homologies was the following: to explain why species A and B share a common feature H (homology), it is assumed that a common ancestor C (which possessed feature H) existed in the past and that both A and B descended from C. Students were also taught to construct explanations for adaptations by referring to natural selection: in a particular environment, some traits provided an advantage to their possessors, contributing to their survival and reproduction, and for these reasons those traits became prevalent in the population. The general form of explanation students were given for adaptations was the following: to explain why species S possesses feature (adaptation) A, it is assumed that S descended from an older population that included both individuals that possessed feature A and others that did not, as well as that this feature provided an advantage to its possessors in the particular environment; as a result those individuals that did not possess A perished whereas those that possessed A survived and evolved to produce species S.[11]

It would be useful to develop an assessment of students' understandings of explanations per se, so that such knowledge could be empirically disentangled from evolution content understanding. For example, ineffective explanation instruction alone (and subsequent student confusion about the utility of explanations) could contribute to poor student performance of evolution explanation tasks. It would be useful to know how the magnitude of explanatory understanding interacts with content knowledge to foster understanding about both microevolution and macroevolution. Regardless, the increasing importance of explanation in science education research and practice will require more explicit and careful integration of HPS perspectives.

Overall, as our discussion of explanation has illustrated, it is clear that different explanatory accounts and different explanatory task structures have yet to be carefully integrated into the teaching and learning of evolution. The development and implementation of HPS-informed conceptual heuristics relating to evolutionary explanations has great potential for improving students' understanding of evolution.

13.5 Conclusion

This chapter has reviewed HPS-informed studies in evolution education dealing with (1) the linkage of particular student ideas to those of prominent naturalists from the history of science (e.g., Lamarck), (2) the characterization of conceptual change in evolution as reflecting paradigm shifts from "Lamarckian" to "Darwinian"

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[11] These explanatory schemes may seem oversimplified but were considered appropriate given the age of students (14–15-year-olds).

worldviews, and (3) unitary perspectives on evolutionary explanation. Collectively, analyses of these selected topics have identified complications with the ways in which HPS ideas have been applied in evolution education scholarship and raised questions about whether these characterizations have clarified or confused thinking about student learning of evolution. Science educators' further engagement with HPS scholars will help to appropriately ground evolution education research, and additional analyses of other facets of HPS scholarship relating to evolution education will be needed in order to build a more robust understanding of how students think about the core topic of evolution (see for example the various chapters in Kampourakis 2013c).

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Chapter 14
History and Philosophy of Science and the Teaching of Macroevolution

Ross H. Nehm and Kostas Kampourakis

14.1 Introduction

In the past decade, increasing scholarly attention and emphasis has been placed on the teaching, learning, and assessment of macroevolutionary concepts (e.g., Catley 2006; Nadelson and Southerland 2010a, b; Padian 2010; Novick and Catley 2012). While the distinctions between microevolution and macroevolution have been topics of lively debate within the history and philosophy of science (HPS) communities for some time, relatively new to the field of science education is the conceptualization of macroevolution as a distinct concept in need of targeted instructional emphasis and research (Catley 2006).

The term *macroevolution* is a relatively recent addition to the lexicon of evolution, first coined (in German) by Filipchenko in 1927 and subsequently recruited into the English language in 1937 by the prominent biologist Theodosius Dobzhansky (Burian 1988). Since its introduction, the meaning of the term macroevolution, like many other biological terms, has changed substantially (see Erwin 2010). Despite these changes, nearly all definitions consider the formation of new species to be an important partition dividing micro- from macroevolution. The US National Academy of Sciences (NAS 2012), for example, defines macroevolution as "[l]arge-scale evolution occurring over geologic time that results in the formation of new species and broader taxonomic groups" and microevolution as "[c]hanges in the traits of a

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group of organisms within a species that do not result in a new species." Importantly, the NAS definitions—and related distinctions in the science education literature (e.g., Catley 2006; Nadelson and Southerland 2010a, b)—focus primarily on *scale* (e.g., within vs. between species; human timescales vs. geological timescales) and *pattern* (e.g., descriptions of large-scale change as opposed to causes of such change). In a similar vein, Catley (2006) highlights the distinction between *short-term* (microevolutionary) and *long-term* (macroevolutionary) change (see also Nadelson and Southerland 2010a, b). While discussions of micro- and macroevolution in the HPS and evolutionary biology literature also focus on scale and pattern, they have paid particular attention to putative factors that *explain* large-scale evolutionary events at different scales of analysis. While natural selection (and other microevolutionary processes) are universally acknowledged as contributors to evolutionary change by biologists, the expansion of possible *mechanisms* accounting for large-scale patterns in the history of life is considered a major advance in evolutionary theory (e.g., Gould 2002). These important distinctions between pattern and mechanism deserve attention, as they have led to a conceptual divergence between the science education and HPS literature.

14.2 Macroevolutionary Patterns and Processes

Macroevolutionary thought has a philosophically rich history (Ruse 1997; Gould 2002; Depew and Weber 1995; Sterelny 2009) and today remains rife with controversy (Dietrich 2010; Erwin 2010). Nonetheless, it is important to point out that many macroevolutionary *patterns* are well established and uncontroversial, such as the reality of mass extinctions (e.g., Jablonski 1986), the originations of now-extinct higher taxa (e.g., Erwin 2010), the evolutionary relationships among all living things (e.g., Hillis 2010), long-term trends in the fossil record (Gould 2002), and evolutionary stasis (e.g., Nehm and Budd 2008). A core macroevolutionary topic of importance to HPS scholars and science educators relates to putative distinctions between large-scale observable patterns in the history of life on the one hand and inferences and theories about the mechanisms responsible for these patterns on the other.

Changes to the definition of *macroevolution* since its introduction in 1927 have in some respects paralleled vacillations between scholarly emphasis on large-scale patterns in the fossil record and their causal underpinnings (e.g., Simpson 1944). Evolutionary biologists from diverse disciplinary backgrounds (e.g., Dobzhansky, Simpson, Mayr, Eldredge, Gould, Gingerich, Futuyma, and Orr) have, like most scientists, recognized that large-scale evolutionary trends, extinctions, and originations of higher taxa do in fact appear in the fossil record (e.g., Simpson 1953; Futuyma 2005; Coyne and Orr 1998; Erwin 2010). But these and many other authors have *disagreed* about whether microevolutionary processes (such as natural selection and genetic drift) are capable of sufficiently accounting for such well-established large-scale patterns (Gould 1985). Causal pluralism, or the expansion of explanatory mechanisms beyond natural selection, is thus a key topic of attention in HPS perspectives on macroevolution. Such plurality is also historically important, as it is considered by some to be divergent from the views of Darwin (1859), who proposed "…natural selection as the single unifying mechanism that causes both micro- and macroevolution" (Travis and Reznick 2009, p. 126).

Evolutionary theorists such as Filipchenko (1927), Goldschmidt (1940), Schindewolf (1950), Eldredge (1989), Stanley (1980), Vrba and Gould (1986), Lloyd and Gould (1993), and Erwin (2010), for example, have adopted what may be termed a causally pluralistic evolutionary worldview and therein argued that distinct macroevolutionary mechanisms (not reducible to microevolutionary processes; e.g., species selection and mass extinction) likely contributed to large-scale evolutionary patterns (Gould 1985; Erwin 2010). Importantly, these authors do not discount the reality or importance of natural selection, but some have questioned its reification as a causal process with all-encompassing explanatory power (Gould 1981; Depew and Weber 1995). Biologists such as Dobzhansky, Simpson, and Futuyma, in contrast, have generally considered natural selection to be a sufficient causal explanation for most macroevolutionary patterns (for a discussion of Simpson's changing views on this matter, see Sepkoski 2008). The views of these scholars are aligned in some respects with those of Travis and Reznick (2009, p. 128), who note: "In the final analysis there is nothing in the fossil record that inherently contradicts Darwin's daring idea that natural selection is the unifying mechanism." In sum, the reality of macroevolutionary *patterns* is simply not in doubt.[1] The controversy in macroevolutionary biology relates to questions about the *processes* involved (natural selection alone or natural selection + other mechanisms).

According to most definitions, the formation of new species (speciation) lies at the boundary between microevolution and macroevolution (e.g., NAS 2012). While the history of biological thought is filled with controversy about the competing roles of natural selection and genetic drift in speciation, many biologists consider the issue to be settled. Coyne and Orr (2004, p. 410), in their seminal treatment of speciation, note: "…firm evidence for the role of genetic drift in speciation is rare." They go on to close the book on this controversy: "It appears, then, that at least one important debate has been settled: selection plays a much larger role in speciation than does drift. It is also worth noting that genetic drift appears to play little part in morphological evolution" (p. 410). In an exhaustive review of the literature, Coyne and Orr summarize a wealth of work indicating that natural selection plays a major role in speciation and that "[i]t is uncontroversial that most phenotypic divergence in ecologically important traits is driven by natural selection" (p. 385). Thus, natural selection is widely considered to play a major role in the speciation process.

Above the species level, the bulk of macroevolutionary debate relevant to the science education community may be formulated as two related questions: (1) Can microevolutionary processes such as natural selection and genetic drift sufficiently account for large-scale patterns in the history of life? If not, what alternative

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[1] Advocates of creationism and intelligent design have repeatedly exploited debates about macroevolution to suggest (incorrectly) that evolution is a theory in crisis and questioned the reality of macroevolutionary patterns because of incompleteness of the fossil record (see Sepkoski 2008). It is important to point out that such incompleteness has not been a topic of equal concern by scientists.

mechanisms are there? And (2) If mechanisms *in addition to* natural selection exist, and they can survive theoretical and empirical testing, how much of the macroevolutionary history of life do they in fact explain (cf. Dietrich 2010)?

Four major macroevolutionary concepts have received considerable scrutiny by evolutionary biologists, paleobiologists, and philosophers of biology over the past 30 years[2]: (1) species selection/sorting, (2) mass extinction, (3) constraints/evolvability, and (4) evolution and development (or "evo-devo"). The important point to keep in mind is that these four concepts, in concert with (or in opposition to) natural selection, could account for large-scale evolutionary outcomes that were unexpected or unexplainable by the exclusive extrapolation of microevolutionary processes over geological timescales. By expanding the range of causal factors contributing to evolutionary change, evolutionary biologists could potentially improve causal precision and eliminate troublesome empirical anomalies. Questions about the validity of these macroevolutionary processes have generated a rich literature in HPS and evolutionary biology. We briefly summarize each in turn prior to investigating their role in science education.

Species selection has become a key feature of modern macroevolutionary theory (Erwin 2010). It is a conceptual outcome of Eldredge and Gould's (1972) formulation of evolutionary "stasis" and "punctuated change." Eldredge and Gould (1972) argued that most species' histories were characterized by the absence of appreciable evolutionary change (i.e., displayed stasis) and that such stability was punctuated by rapid morphological evolution associated with cladogenesis (lineage splitting speciation) (Nehm and Budd 2008). This model was offered in opposition to what Eldredge and Gould (1972) viewed as the prevailing evolutionary orthodoxy of the time: slow, continuous change. Eldredge and Gould's alternative model nicely framed the question of whether species could be thought of as *individuals*. That is, in the punctuated model, if species have stability in time and space (a "life span"), and are demarcated by clear beginnings (punctuations associated with "birth") and clear endings (extinction or "death"), could they not have species-level traits that could be selected, in a way analogous to how individual organismal traits are selected (for the conception of species as individuals, see Ghiselin 1974; Hull 1980)?

Several empirical and philosophical studies of this new conceptualization of species-level selection have been conducted (e.g., Jablonski and Hunt 2006; Hull 1980). These studies generally support the view that species may display properties that are not reducible to lower hierarchical levels, that is, properties that are not aggregates of lower-level phenomena (Stanley 1980; Sepkoski 2008). Geographic range has long been considered a species-level, variable, and heritable trait (Jablonski and Hunt 2006). Philosophers and paleobiologists have debated these empirical cases at length and agree to some extent that species-level selection is theoretically possible (Hull 1980; Sepkoski 2008). Despite being conceptually and philosophically important, so few empirical cases of species selection have been confirmed that the relative significance of this macroevolutionary process appears

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[2] This list is by no means exhaustive (see Ayala and Arp 2010).

to be small (Dietrich 2010). In sum, while species selection may be viewed as a unique and distinctly macroevolutionary mechanism accounting for large-scale evolutionary patterns, the range of phenomena that it might actually explain is quite limited at present.

Like species selection, mass extinctions have been considered to be a central macroevolutionary process (Jablonski 1986). Mass extinctions are important in macroevolutionary thought because they have been thought to cause conceptual complications for extrapolationist accountings of macroevolutionary patterns (e.g., Raup 1994). Mass extinctions have the potential to counteract the smaller scale workings of natural selection; reproductive success and differential survival during "normal" times may have little association with reproductive success and differential survival during times of mass extinction (Jablonski 1986). For example, while patterns of differential survival over millions of years may produce well-adapted animals of large body size, during geologically brief episodes of mass extinction (e.g., the end Cretaceous event), differential survival may favor animals of small body size thereby counteracting this adaptive trend. Mass extinctions therefore raise the possibility that microevolutionary processes alone cannot sufficiently account for large-scale patterns in the history of life (Erwin 2010). The (potentially stochastic) pruning of lineages during mass extinctions may "reset" the playing field for lineages, counteracting the effects of adaptive microevolution. As noted by Raup (1994, p. 6758): "Except for a few cases, there is little evidence that extinction is selective in the […] sense argued by Darwin." In this view, natural selection cannot sufficiently account for macroevolutionary patterns; mass extinction must be considered as an additional causal factor that can work in opposition to natural selection.

A third macroevolutionary topic in the HPS literature is constraint and evolvability (Gould 2002; Erwin 2010; Minelli and Fusco 2012). While linking constraint and evolvability is questionable in some respects, both acknowledge the important roles that genetic, architectural, historical, developmental, and functional constraints may play in limiting the types of long-term evolutionary change that can occur (cf. Gould 2002, p. 1059; Erwin 2010). Gould sees particular patterns of macroevolutionary repetition (i.e., parallelism) as evidence of the importance of internal constraints. These constraints are significant in a macroevolutionary sense because they may "push back" against the actions of natural selection and thereby limit pathways of evolutionary change. Put another way, limits on variation (caused by internal constraints) channel pathways of evolutionary change by limiting the options that selection has available to work with. Gould (2002) argues that this perspective is important relative to macroevolutionary theory because constraint helps to explain macroevolutionary patterns that cannot be accounted for by selection alone (see also Bateson and Gluckman 2011 for a more recent discussion). Such views also resonate with many perspectives from evolutionary developmental biology (e.g., Sansom and Brandon 2007; Love 2007, 2013).

Gould's perspectives align in many ways with the large body of work by Brian Goodwin (reviewed in Goodwin 2009). He challenges the notion that random genetic variation can (or does) generate an infinite variety of options for natural selection to work with, and so natural selection is not the only factor explaining discrete (vs. continuous) distributions of morphology in time and space. Evidence for this perspective may be found in David Raup's "morphospace" diagrams (see Raup and Stanley 1978). These diagrams map the morphologies of extinct and extant species within the universe of forms that could theoretically exist. Comparing actual vs. possible shell shapes, for example, illustrates that some regions of morphospace are densely populated, whereas others are sparse. Desolate regions of morphospace are fertile ground for exploring the question of whether such forms are impossible to generate or merely have yet to evolve.

Although Erwin's (2010) perspective on evolvability differs somewhat from those of Gould (2002) and Goodwin (2009), it also considers limits on the pathways that evolution can take. Erwin sums up his perspective of "evolvability" when he writes: "…the structure of gene regulatory networks in animals […] indicates that the nature of the variation available for selection to act upon has changed over time…[and] this may impose another way in which macroevolutionary patterns are not reducible to microevolutionary processes, at least as they are currently defined by microevolutionists" (Erwin 2010, p. 189). He goes on to note "What is strikingly absent from virtually all microevolutionary thought […] is a sense of history, of the impact of evolutionary changes on the range of variation that is possible, and of how that range of variation has itself changed over time" (p. 191). Thus, Erwin and others have viewed the concept of "evolvability" as a uniquely macroevolutionary idea.

The fourth topic that has received considerable attention in the HPS literature relating to macroevolution is evolutionary developmental biology (informally referred to as "evo-devo") (Carroll 2005a, b). As noted by Raff (2000, p. 74) "evolutionary change occurs not by the direct transformation of adult ancestors into adult descendants but rather when developmental processes produce the features of each generation in an evolving lineage." Although for centuries naturalists have seriously considered the significance of this point (e.g., von Baer 1828; Darwin 1860[3]; Haeckel 1868; Goldschmidt 1940; Simpson 1944; Schindewolf 1950; Waddington 1970), the role that development has played in macroevolutionary thought has varied dramatically through history (see Gould 1977 for a review). Mayr (1988) argued that development was largely excluded from the "evolutionary synthesis" of the 1940s (see Futuyma 1998 for an alternative view) and subsequently remained somewhat isolated from evolutionary theory (at least in the United States; see Lloyd and Gould's (1993) preface to Schindewolf (1950/1993) for a more global perspective). This situation changed with Gould's forceful reintroduction of the importance of development to macroevolution in *Ontogeny and Phylogeny* (1977). Therein Gould reframed the complex historical literature on evolution and development, crafted a new (largely morphological) framework for

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[3] "Embryology is to me by far the strongest single class of facts in favor of change of forms…" Darwin, September 10, 1860, letter to AsaGray.

heterochrony and heterotopy,[4] and paved the way for the modern resurgence of interest in evo-devo that has yet to peak[5] (Carroll 2005a, b).

More recently, the conceptual framework of evo-devo has been further expanded to encompass the genetic underpinnings of largely pattern-based (e.g., heterochrony and heterotopy) changes in the evolution of development. More process-oriented frameworks include heterometry, which refers to an evolutionary change in the amount of a gene product, and heterotypy, which refers to an evolutionary change in the nature of a gene product (Arthur 2004, pp. 81–83). The revolutionary advances in regulatory genetics and genomics has transformed modern evo-devo into a mechanistic science (Carroll 2005a, b). Indeed, the remarkable patterns of evolutionary developmental parallelisms that have fascinated naturalists for centuries are at last being linked to biological processes at the molecular, cellular, and developmental levels (e.g., von Baer 1828; Haeckel 1868; Goldschmidt 1940; Schindewolf 1950; Gould 1977).

Key questions in evo-devo include the study of how gene networks govern ontogeny, the factors that make developing systems robust enough to tolerate mutations that change the course of development, how the rules that govern ontogeny constrain the production of new phenotypic variation, how development influences speciation, and the origins of body plans and their evolvability[6] (Raff 2000; Arthur 2004; Carroll 2005a, b; Minelli 2009). As noted by Minelli and Fusco (2012): "Overall, developmental processes can contribute to speciation and diversification at different stages of the speciation process, at different levels of biological organization and along the organism's whole life cycle." The explosion of empirical findings in evo-devo over the past decade, along with new journals (e.g., *Evolution & Development*), professional societies, and faculty positions devoted to the subject, is suggestive of major changes to the structure of evolutionary biology.

Despite the growing importance of evo-devo for evolutionary studies, and increasing interest in the topic in HPS (e.g., Love 2013), evo-devo has not received concomitant attention in science education research or practice (from the perspective of curriculum or pedagogy; see Love [in press] for a view on both of these issues from a HPS perspective).[7] Equally concerning is the fact that evo-devo is conspicuously absent from science educators' recent conceptualizations of the macroevolution construct and associated features deemed worthy of assessment (e.g., Catley 2006; Nadelson and Southerland 2010a, b; see also Novick and Catley 2012). Surprisingly, even Padian's (2010) vociferous plea for the inclusion of macroevolution in K-12

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[4] Evolutionary changes in developmental timing and spatial arrangement, respectively; see Zelditch (2001) for morphological (pattern-based) perspective and Arthur (2004) for a more mechanistic perspective.

[5] The institutionalization of evo-devo took place in 1999 when it was granted its own division in the Society for Integrative and Comparative Biology (SICB), as well as through the National Science Foundation's establishment of a separate division for funding evo-devo research.

[6] See Müller (2007, pp. 505–506) for a more complete conceptual and historical synopsis.

[7] Although of course there are exceptions. See, for example, a special issue of the journal *Evolution Education and Outreach* (June, 2012).

education lacked explicit mention to the role that evo-devo might play. Thus, evo-devo serves as another example in which current perspectives from HPS have yet to influence the teaching, learning, and assessment of macroevolution.

Our overview of some (but by no means all) of the key macroevolutionary ideas emphasized in the HPS literature—species selection, mass extinction, constraint/evolvability, and evo-devo—and those that have contributed to the resurgence of empirical macroevolutionary inquiry (i.e., the so-called paleobiological revolution of Sepkoski and Ruse 2009) provides a vantage point from which to examine scholarship about the teaching, learning, and assessment of macroevolution in the science education literature. As will become readily apparent, despite some similarities, the two communities have envisioned macroevolution in strikingly different ways.

14.3 Macroevolution: Science Educators' Blind Spot?

Science education research relating to macroevolution has thus far focused on three major issues: (1) general advocacy for the teaching of macroevolution in K-12 education (and cladograms in particular) (Catley 2006; Padian 2010), (2) measurement of students' macroevolutionary knowledge (Dodick and Orion 2003; Nadelson and Southerland 2010a, b; see also Novick and Catley 2012), and (3) investigations of students' beliefs about small-scale vs. large-scale evolutionary change (Nadelson and Southerland 2010a, b). The intrusion of creationist challenges, spurred on by scholarly debates about macroevolution, is also in need of consideration. We begin with a review of advocacy for the teaching of macroevolution in the science education community.

A provocative opinion piece by Kefyn Catley in 2006 was in many respects a "call to arms" for the science education community to acknowledge and explicitly incorporate macroevolution in science education. It bemoaned the lack of focus on macroevolution in science education teaching and research and chastised educators for their near-exclusive focus on natural selection (and associated research on misconceptions about natural selection alone). Catley emphasized that "[w]ithout a clear perspective on macroevolution, an understanding of the full spectrum of evolution is simply not possible. This notwithstanding, microevolutionary mechanisms are taught almost exclusively in our schools, to the detriment of those mechanisms that allow us to understand the larger picture" (Catley 2006, p. 768). In perhaps his most controversial claim, Catley states: "Knowledge of natural selection, while vitally important, explains little about the incredible diversity of species on the planet" (2006, p. 775). Hence, Catley appears to take a stance that is more closely aligned with what we have termed causal pluralism (see above)—that there is more to the evolution of life than natural selection alone. But in addition to natural selection, what, in Catley's view, explains macroevolutionary change?

An interesting aspect of Catley's (2006) perspective is that it lacks mention of the key macroevolutionary concepts (species selection, mass extinction, constraints/evolvability, and evo-devo) that have been central to HPS scholarship (e.g., Sepkoski 2008; Erwin 2010). In fact, it does not clearly outline any causal alternatives to natural selection. This generates a conceptual void: What are we to make of a "call to arms" for the teaching of macroevolution that downplays the importance of natural selection on the one hand ("By themselves, the products of the "New Synthesis" do not adequately account for the history of life or for its diversity" (Catley 2006, p. 770)) but fails to mention hierarchical selection theory or many of the classic macroevolutionary ideas proposed by Stanley, Gould, Eldredge, Vrba, and Lloyd? If one considers Catley's (2006) perspective from a pattern-based perspective, however, the exclusion of natural selection, species selection, mass extinction, and constraint and evolvability may be reasonable; students need to learn about large-scale patterns and, according to Catley, learn these patterns through the lens of phylogenetic systematics, or cladistics.

One aspect of Catley's stance on macroevolution is in alignment with the causal pluralists (cf. Gould 1985). Specifically, he appears to take the position that species are properly conceptualized as "real" individuals (Catley 2006 repeatedly notes that species are "the very units of evolution"). Yet, interestingly enough, he makes no mention of the past 30 years of discussion relating to species selection or how it should be conceptualized in teaching and learning about macroevolution.

A central piece of Catley's (2006) argument appears to be that cladograms must be integrated into the teaching and learning of evolution and, by doing so, macroevolutionary content will be properly addressed. Cladograms are representational diagrams illustrating the evolutionary relationships of biological units (e.g., species and clades) generated using the underlying methodology of Willi Hennig (i.e., Cladistics; see Hennig 1999). They depict evolutionary *patterns* (characters and their various states across operational taxonomic units, such as species, groups partitioned based upon their recent common ancestry, and outgroups to polarize character state transformations). Cladograms are powerful tools for testing causal hypotheses (such as the "randomness" of mass extinctions), but themselves represent patterns of evolutionary relationship. Therefore, they are tools for articulating patterns in the natural world (the differential birth and death of species within and among clades) with tests of theory (e.g., selection of species in these clades). Macroevolutionary theory and its causal foundations are not necessarily addressed by using or teaching about cladograms (except, perhaps, patterns of cladogenesis), however central they may be to scientific practice. While cladograms have been increasingly employed in evolution research, it is important to point out that the major theoretical advances in macroevolution predated the widespread adoption of phylogenetic taxonomy in the United States (Hull 1988). In sum, while cladograms are now central tools in evolutionary biology, as noted by Catley, by themselves they do not say much about macroevolutionary processes and mechanisms, but only represent patterns.

A recent article by Kevin Padian (2010, p. 206) echoes Catley's (2006) concerns with teaching macroevolution: "Macroevolution must take a much more prominent place in K-12 science teaching. To do so, a curriculum must be redeveloped at both K-12 and college levels, so that preparation in macroevolution is a required part of K-12 biology preparation." He also takes aim at his scientific colleagues: "…few evolutionary biologists have a first-hand understanding of macroevolution, and they do not spend substantial time on it in their college courses. This is because most of them are population biologists and population geneticists, and they have had little or no training in macroevolution." Padian also targets science textbooks: "…textbooks in all grades from K-16 fail completely to convey an understanding of how evolution works in the long run."

Catley (2006) and Padian (2010) raise several important points worthy of empirical consideration. First, is macroevolution receiving short shrift in evolution education? Is Catley correct when he claims that "As currently taught, natural selection stops short of fostering an understanding of its effects over time on species themselves, or on cladogenesis. It concentrates almost exclusively on processes that occur within individuals and populations" (Catley 2006, p. 775)? Have aspects of macroevolution in fact been covered in secondary and undergraduate textbooks and curricula? While it is challenging enough today to determine the degree to which particular topics are emphasized in science classrooms, the problem becomes much more difficult to address in the history of science education. One long-standing approach for documenting topical emphasis in the history of science education is to examine textbook content and structure (Cretzinger 1941; Skoog 1969; Moody 1996; Nehm et al. 2009). A surprising number of studies have investigated how evolutionary biology has been conceptualized and represented in textbooks over the past century (for a historical review, see Skoog 1969 and Moody 1996). These studies provide one empirical approach for attempting to answer the relatively straightforward question "Is macroevolution being taught?" Given that Catley's claim is directed at US education, our review is restricted to that context.[8]

It is clear that many of the concepts that Catley (2006) mentions have been included in biology textbooks in the United States for at least 100 years, although, as mentioned above, this does not necessarily mean that they were covered in classroom instruction. Moreover, it is clear that the term "macroevolution" is a relatively recent addition to the lexicon of evolution, and many texts do not explicitly use this term even if they discuss ideas that are widely considered to be macroevolutionary in nature (e.g., horse evolution). In some of the earliest biology textbooks produced in the United States (from the period of 1900 to 1919), large-scale evolution (between-species change, or transformation) was "…a common topic as it was discussed in five of the eight textbooks" [sampled] (Skoog 1969, p. 151). Other topics present in this early period included "convergent evolution," "evolutionary relationships," "fossils and other remains," and the "evolution of birds" (Skoog 1969). Species transformation again appears as one of the more common topics in textbooks from 1920 to 1929, with the evolution of horses being a particularly common macroevolutionary example[9] (Skoog 1969). Similar patterns were noted through the 1960s (when natural selection was noted to occur in all of Skoog's textbook samples; see Fig. 14.1). In a similarly detailed analysis of 17 evolutionary subtopics in early textbooks, Nicholas (1965) found that paleontological evidence from the

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[8] While English-language textbooks (particularly from the United States) have received the most attention in the science education literature, it is important to point out that international studies of evolutionary content in textbooks have also been completed. See, for example, Swarts et al. (1994) for a discussion of textbooks from China and the former Soviet Union.

[9] Although one that has more recently been reconceptualized as a branching, rather than as a linear, evolutionary pattern.

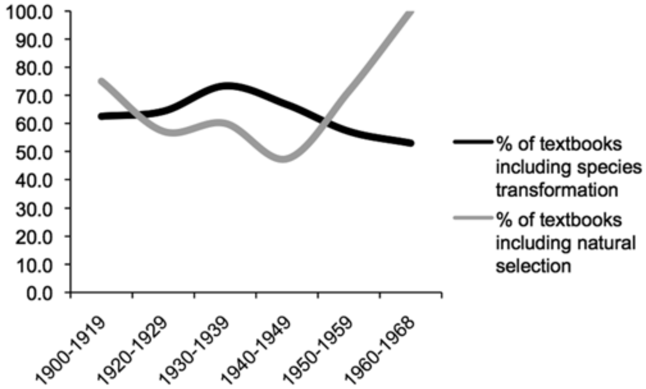

Fig. 14.1 Macroevolution in science textbooks 1900–1968. Based on Skoog's (1969) analysis of evolutionary content in textbooks from 1900 to 1960, species transformations (macroevolutionary change, according to most definitions; see text) were included at generally comparable levels as natural selection until the 1960s, when natural selection was included in all sampled texts

fossil record was the most commonly covered evolutionary subtopic. Other frequently included topics that could reasonably be considered to have a macroevolutionary slant were "rates of evolution," "influence of the physical history of the Earth on evolution," and the "evolutionary history of man [sic]." This work is in alignment with Skoog's general findings.

More recent studies of best-selling undergraduate biology textbooks revealed that all of them cover macroevolution (Nehm et al. 2009). If the evolutionary history of particular clades is also considered, macroevolution is well represented, albeit segregated to particular chapters (Nehm et al. 2009). Importantly, however, macroevolution is more than tallying long-term patterns of life's "comings and goings" (Padian 2010); macroevolutionary *processes* are indeed underrepresented in these undergraduate textbooks. In high school textbooks, coverage of macroevolution is difficult to ascertain given that ostensibly macroevolutionary topics, such as punctuated equilibrium, have been lumped with other topics in some empirical studies (e.g., Rosenthal 1985). Nevertheless, it is apparent that many topics that fit under the conceptual umbrella of macroevolution were covered in more recently published textbooks (Skoog 1984; Rosenthal 1985). Given that textbooks "…have much influence on what is taught" (Skoog 1984, p. 127), this finding lends credence to the idea that macroevolution has had a consistent home in biology curricula for a century or more. Nonetheless, it may be true that the proportion of macroevolutionary content is too small (Padian 2010).

The US *National Science Education Standards* (1996) may also be used to examine the status of macroevolutionary ideas in biology education. The *Standards* contain at least ten evolutionary ideas, half of which may be reasonably interpreted as macroevolutionary in nature: (1) common ancestry of species; (2) classification systems reflect evolutionary relationships; (3) the fossil record, large-scale changes in life, and extinction; (4) similarities among diverse species; and (5) geological time, or deep time. Overall, there is remarkable similarity between concepts in the *Standards* and the macroevolutionary concepts that Catley (2006) and Padian (2010) suggest are lacking in emphasis. Nonetheless, the *Standards* do *not* include the key causal features emphasized in recent HPS scholarship, such as species selection, mass extinction, and constraints on the evolution of form, evolvability, and evo-devo.

In addition to textbooks and the US *Standards*, practitioner journals (such as the widely subscribed *American Biology Teacher*) may be examined to explore the degree to which macroevolution has been addressed in the professional community. Many articles have discussed the importance of teaching both macroevolutionary patterns *and* processes, such as punctuated equilibrium (Alters and McComas 1994); rapid, large-scale morphological and molecular evolution in stickleback fish (Platt 2006); rates of macroevolution (Marco and López 1993); and macroevolution in the fossil record (Dodick and Orion 2003). But on review of the evolutionary topics covered in *ABT*, it is clear that specific macroevolutionary focus is comparatively less than treatments of natural selection and genetic drift. Perhaps the most interesting observation in reviewing the literature is that discussions of *causal* factors relating to macroevolution are extremely rare. So, in many respects, Catley (2006) is correct that macroevolution (at least as HPS scholars' conceptualize the topic, cf. Sepkoski 2008) has received short shrift in science education. But it is also true that facets of Catley's (2006) version of macroevolution are clearly present.

Despite the concerns mentioned above, Catley's (2006) standpoints on macroevolution have without question stimulated a new and innovative research program focusing on student reasoning about phylogenetic and macroevolutionary *patterns* (particularly the interpretation of cladograms) (Baum and Offner 2008). Interpreting cladograms, and using them to reason about evolution (micro- or macroevolution), involves aspects of visual reasoning, hierarchical thinking, abstract representation, misconceptions about evolution, and the nature of science (e.g., cladograms represent testable hypotheses). Given that cladograms have become de rigueur for testing patterns and processes of micro- and macroevolutionary change (e.g., pinpointing likely hosts of the SARS coronavirus, HIV subtype evolution, and the coevolution of angiosperms and their pollinators), this research direction is critically important for the field of science education. What have been lacking in this research program are discussions of the causal *processes* that many HPS scholars consider to be uniquely macroevolutionary, such as species selection, mass extinction selectivity, and clade/group selection (Sepkoski 2008). For some HPS scholars and evolutionary biologists, these ideas form the core of macroevolutionary theory and the most significant conceptual advances since Darwin (Gould 1981, 2002). Yet, it is precisely these concepts that remain conspicuously absent from the science education research literature about macroevolution.

14.4 Measuring Macroevolutionary Knowledge

Given the importance of macroevolution in science education, the question arises as to how to determine if students are learning it. A broad array of empirical research questions in evolution education requires the use of measurement instruments designed to capture latent constructs, such as students' knowledge of macroevolution or their belief in evolution. In recent years, some science educators have raised concerns about the quality of extant instruments used in science education research in general and evolution education in particular (Nehm 2006; Smith 2010; Neumann et al. 2011). It is critically important that the evolution education research community develops and deploys high-quality instruments that are in alignment with professional measurement standards (i.e., AERA et al. 1999). Otherwise, the measures derived from such instruments will have little meaning, or, more problematically, they may mislead educators in their efforts to improve the teaching and learning of core scientific topics such as evolution. Instruments about macroevolution are no exception.

Nadelson and Southerland (2010a, b) developed the first instrument designed to measure students' knowledge of macroevolution.[10] Several compelling reasons justified the development of this instrument. First, school and university students (and the general public) appear to have different levels of acceptance relating to microevolutionary and macroevolutionary change. Second, many science curricula and textbooks distinguish microevolution and macroevolution as distinct instructional topics (e.g., Stanley 1980). Third, understanding microevolutionary processes (i.e., natural selection and genetic drift) may not translate into an understanding of, for example, larger scale phenomena, such as the formation of new species or evolutionary trends (Catley 2006). Fourth, Nadelson and Southerland (2010a, b) argue that natural selection and adaptation are primarily microevolutionary, and not macroevolutionary, concepts (contrary to the views of some, see above and Table 14.1). Thus, despite several microevolutionary knowledge measures (e.g., Settlage and Odom 1995), a distinct measure of macroevolutionary knowledge appeared to be justified. Given the controversies in the HPS literature about how macroevolution should be conceptualized, to what extent does Nadelson and Southerland's (2010a, b) construct of "macroevolution" align with HPS perspectives?

In designing their instrument for measuring undergraduate students' knowledge of macroevolution, Nadelson and Southerland (2010a, b, p. 156) "…identified deep time, phylogenetics, speciation, fossils, and the nature of science as five essential concepts necessary to comprehend macroevolution." Natural selection is notably absent. The content of the test was established by "…feedback from professional biologists and evolution educators," a review of textbooks, and an expert review revealing that "[e]ach of the five faculty members considered our subscales to be representative of the major topics and concepts associated with macroevolution" (Nadelson and Southerland 2010a, b, p. 156). In one of their open-ended instrument items, they chose to focus on speciation "…because it is often the most contentious concept related to macroevolution" (p. 161). It is by no means clear if HPS scholars would agree that *speciation* is more contentious than, for example, constraints or species selection.

Nadelson and Southerland's (2010a, b) macroevolution instrument uses a "scenario-based" approach, in which students must use information on the assessment to choose among answer options (one scientifically correct, the others

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[10] Albeit one that has received considerable criticism. See, for example, Novick and Catley (2012).

Table 14.1 What does the construct of "macroevolution" include? A synopsis of some views from the HPS and science education literatures. See text for details and discussion of causal vs. pattern-based perspectives. Note that discussions in the HPS literature are not explicitly aligned with any educational grade band (n/a)

HPS literature	Padian (2010)	Catley (2006)	Nadelson and Southerland (2010a, b)
Educational level: n/a	Educational level: K-16	Educational level: K-16(?)	Educational level: undergraduate
Natural selection's ability to explain macroevolution (e.g., Gould 2002; Sepkoski 2008)	As a species lineage evolves, its morphology may change in many ways or hardly at all (see discussion, p. 208)	Knowledge of natural selection, while vitally important, explains little about the incredible diversity of species on the planet (p. 775); by themselves, the products of the "new synthesis" do not adequately account for the history of life or for its diversity (p. 770)	Unclear: "…understanding of speciation by natural selection, a fundamental process in macroevolution" (p. 175); "…natural selection and adaptation, which are primarily interpreted as microevolutionary concepts" (p. 155)
Species as individuals; species-level traits (e.g., variability, geographic range); species selection, species sorting, group selection (e.g., Hull 1980; Lloyd and Gould 1993)	The rates of origination and extinction of *species* shape the history of life (p. 207)	Species radiations, based on novel evolutionary characters; cladogenesis; formation of higher taxa (p. 769); species exist in both space and time, and in addition to being the fundamental elements of Linnaean classification, they are also the *units of evolution* and biodiversity (p. 775)	Speciation: long-term speciation can be considered to be a key concept that should be included in a measure of macroevolution understanding (p. 158)
Mass extinction selectivity/stochasticity (e.g., Jablonski 1986; Sepkoski 2008)	Extinctions are studied at two levels: background and *mass extinctions* (p. 208)	Pattern-based extinction (throughout)	Pattern-based mass extinction: diversity of life decreases and increases with events such as mass extinctions (p. 168); an examination of extinction using diagrams of lineages (p. 160)
Constraint, evolvability, and contingency (e.g., Gould 2002; Goodwin 2009; Erwin 2010; Kirschner and Gerhart 1998)	Not explicitly considered	Not explicitly considered	Not explicitly considered
Evo-devo (e.g., Gould 1977, 2002; Raff 1998; Carroll 2005a, b; Arthur 2004; Minelli 2009)	Not explicitly considered	Not explicitly considered	Not explicitly considered

incorrect). Several macroevolutionary patterns are used to frame the instrument answer options: (1) using an evolutionary tree, exploring the *processes*[11] involved in the transition of the whale "family" from ancient shore-dwelling ancestors; (2) interpreting the evolution of eyes, including a discussion of variation in extant mollusk lineages; (3) interpreting extinction patterns using "diagrams of lineages"; (4) examining "evolutionary pathways of the African Great Ape" and the development of what they term "diagram pathways"; and (5) interpreting geographic distributions of fossils on different continents. To varying extents, the scenarios test students' understandings of the five ideas that Nadelson and Southerland (2010a, b) consider to be uniquely "macroevolutionary": phylogenetics, speciation, deep time, fossils, and the nature of science.

While we suspect that most biologists and philosophers of biology would agree with Nadelson and Southerland (2010a, b, p. 175) when they write, "Assessing learner knowledge of macroevolution is essential for developing and honing science curricula that are effective in helping students develop an understanding of this fundamental aspect of biology," the discordance between the HPS literature—and other literature in science education—and their concept of macroevolution is notable. In particular, the exclusion of selection and drift as causes of macroevolution (along with the absence of hierarchical selection theory, species selection, constraints/evolvability, evo-devo) are noteworthy gaps. Overall, it is apparent that some science educators are approaching the measurement of students' knowledge of macroevolution in a unique way, excluding the key features of macroevolution discussed in the HPS literature. The question is whether other education stakeholders conceptualize macroevolution similarly.

14.5 Future Directions in Macroevolution Education

Given the rich literature in HPS relating to macroevolution, it would be useful for teacher educators, instrument developers, curriculum designers, and science education researchers to engage more fully with this work. Our review has revealed several issues that would benefit from a more integrated approach. These include (1) recognizing that natural selection is widely acknowledged to be a major causal process in the generation of macroevolutionary patterns (particularly speciation), that is, constructs of macroevolution should not exclude the theory of natural selection (*contra* Nadelson and Southerland 2010a, b); (2) emphasizing macroevolutionary processes, such as species selection, mass extinction, constraint/evolvability, and evo-devo as core macroevolutionary topics (Table 14.1); (3) developing a consensus definition of macroevolution, associated key standards (i.e., phenomena and processes), and disciplinary practices (i.e., ways of thinking and reasoning,

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[11] However, no processes (e.g., natural selection, drift, species selection) are offered as answer options on the assessment.

sensu Love 2013) that are appropriate for K-12 students; (4) performing studies of students' knowledge of macroevolutionary phenomena and their reasoning about the processes that might account for those phenomena; (5) linking Catley and colleagues' innovative work on cladogram interpretation with *causal* hypothesis testing. Such work has great potential in integrating a large body of work on microevolution and natural selection with macroevolutionary patterns and causes; (6) exploring how complex system thinking and hierarchical thinking relate to the transfer of natural selection understanding to broader temporal scales; such work is wanting but would add a new dimension to a growing body of work on complex systems (e.g., Wilensky and Resnick 1999). Overall, as envisioned by science educators, macroevolution is a messy amalgamation of phenomena, concepts, and processes united by a weak conceptual framework (e.g., vague notions of "scale"). Currently, the inconsistencies between how the HPS and science education communities envision macroevolution are dramatic, and as a consequence a shared vision of macroevolution is lacking.

14.6 Conclusion

The teaching and learning of macroevolutionary ideas, perhaps more so than other science topics, is tightly bound to the history and philosophy of science (HPS). Nevertheless, as our chapter has illustrated, many studies in evolution education have not fully engaged with HPS scholarship, particularly the topics of species selection, mass extinction, constraint/evolvability, and evo-devo. Currently, science educators' conceptualization of "macroevolution" consists of a messy amalgamation of phenomena, concepts, and processes united by a weak conceptual framework (e.g., vague notions of "scale"). Inconsistencies between how the HPS and science education communities envision macroevolution are dramatic and prevent meaningful progress in the teaching and learning of this important area of evolution.

In closing, after taking stock of the perspectives on macroevolution from HPS, the science education research literature, practitioner journals, and creationist tactics, how should macroevolution be envisioned by science educators and delivered instructionally to students (if at all)? Sepkoski may have provided one of the more reasonable answers to this thorny question when he wrote: "There is no reason to fear teaching schoolchildren that drift, mutation, and natural selection form the central pillar of evolutionary theory, any more than it is dangerous to teach Newtonian mechanics in high-school physics classes. Like quantum mechanics, the current complex debates in macroevolutionary theory are appropriately taught after the basic framework has been established, since they build on, but not invalidate, the foundation" (2008, p. 234). As our review has demonstrated, contemporary views of macroevolution in the HPS community encompass much more than pattern recognition and cladogram interpretation, do not discount the role of natural selection, and offer a more expansive perspective on the range of causal processes that may be responsible for the grand history of life on earth.

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Chapter 15
Twenty-First-Century Genetics and Genomics: Contributions of HPS-Informed Research and Pedagogy

Niklas M. Gericke and Mike U. Smith

15.1 Introduction

Empirical studies have shown that genetics is considered to be the most difficult subject of biology to teach and to learn (Bahar et al. 1999; Finley et al. 1982; Johnstone and Mahmoud 1980). Moreover, genetics is the cornerstone of any evolution curriculum and thus the basis for any study of biology. Genetic education research has therefore evoked great interest over the years. The field of research in genetics is one of the most rapidly developing sciences of the last century with great impact on society and media due to new biotechnologies such as genetically modified organisms (GMO), genetic screening, forensics, and high-profile ventures such as the Human Genome Project. Because of the exponential knowledge development in genetics, many major advances have occurred in the conceptual understanding of genetic phenomena[1] attracting great interest from scholars in the history and philosophy of science (HPS). At the center of the development of genetics is the circuitous route to our current understanding of the concept of the gene, resulting in the current polysemous and sometimes incoherent current view. Associated with this historical development are important biological philosophical issues such as reductionism, genetic determinism, and the relationship between function and structure.

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[1] See, for example, Beurton and colleagues (2000), Davis (2003), Falk (2010), Keller (2005), and Sapp (2003).

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This article is divided in two main sections: (1) a condensed overview of the historical development of genetics and the philosophical implications of this development and (2) a review of genetics education research, focusing on how it is informed by issues from HPS. We identify contributions of HPS-informed genetics education scholarship to the following: (1) teaching and learning genetics, (2) teaching about the nature of science, (3) humanizing science, and (4) enhancing reasoning, argumentation, and thinking skills. Finally we give some concluding remarks and suggestion for future research.

15.2 History and Philosophy of Genetics

Questions about genetics are probably as old as sentient beings: "Where did I come from?" "Why do I have blue eyes?" "Why are some people just born to be better than other people at some things?" "Where did all the different species come from?" Genetics interests everyone from the man on the street to scientists, philosophers, and historians. As a recognized field of study, genetics is a relatively young science—only about a century old and is perhaps the most rapidly growing field of science today. The emergence of genetics is a fascinating story, and at the center of this story is the hunt for the gene, the most central concept of genetics. The gene has been operationally defined on the basis of four interdependent phenomena: genetic transmission (inheritance of traits from one generation to the next), genetic recombination (generating new combinations of traits), gene mutation (changes in DNA that generate new traits), and gene function (Portin 1993). Over the course of its history, genetics research and genetic applications have focused on each component to differing degrees. In this section we begin with an overview of the search for and the differing understandings of the concept of the gene. This history is provided because an understanding of the history of genetics (as seen through the lens of the gene concept) can be beneficial for understanding not only how to identify and address historical and philosophical issues that arise in genetics education but also how to promote effective instruction.

15.2.1 History of Heredity Before Genetics

The idea of biological heredity is an ancient concept based on experience with humans, as well as domestic animals and crops. The oldest known pedigree (associated with horse breeding) was found in Mesopotamia and is over 5,000 years old (Gustavsson 2004). The Talmud, one of the ancient holy books of the Jews, prohibits circumcision of sons to women who have previously given birth to children that bled to death, as well as the sons born to sisters of such mothers. Clearly, practical insight based on genetics understanding is ancient (Gustavsson 2004). The origin of formal genetics can be dated to about 1900 with the independent recognition of

Mendel's earlier work by Correns, de Vries, and Tschermak von Seysenegg (Moore 2001), although the contribution of von Tschermak Seysenegg has been questioned in recent years (Henig 2000; Olby 1985). The routes to classical genetics come from research in evolution, cytology, embryology and reproduction, breeding, and hybrid formation (Carlson 2004). These research areas had different aims but in different ways addressed questions that from the twentieth century and onwards would become intimately tied to the new field of genetics.

Questions about the origin of species became prominent in the eighteenth century. The predominant belief before that time was essentially the view of the church that all species are the products of divine creation. This view began to be vigorously challenged as a result of the French Enlightenment's demand that the answers to questions about the natural world be sought through the application reason, observation, and experimentation rather than faith. Prior to Darwin and Mendel, heredity was generally thought of in terms of blending rather than being particulate (Uddenberg 2003). During this time, evolutionary explanations came to be more acceptable accounts of the origin of species. Lamarck proposed a theory of evolution in which the characteristics of an organism change in response to its behavior and changes in its environment. Although he recognized a role for heredity in the process, heredity was not of central importance to Lamarck's explanations.

By contrast, heredity played a central role in Darwin's theory of evolution, as a way of explaining the variations on which natural selection acts to produce new species. Darwin called his provisional theory of heredity pangenesis. This theory suggested that small units, which he called "gemmules," are produced by the cells, that these gemmules migrate throughout the body to produce the inherited traits, and that some gemmules are retained in the reproductive tissues in the gonads and thus are passed from one generation to another (Darwin 1868). Although the theory had little experimental support, it clearly recognized the transmission of genetic material (or at least, material affecting heritable traits) from one generation to the next. Darwin's pangenesis theory, however, held that the gemmules might be changed by external conditions, i.e., accepted the inheritance of acquired characteristics, an idea that Darwin's cousin Francis Galton strongly opposed.[2]

Cytology, the study of the cell, was made possible by Janssen's invention of the first compound microscope in the early seventeenth century. However, it was not until 1838 that Schleiden proposed a theory arguing that plants are communities of cells. Scientists promptly turned their attention to the contents of the cell; Huxley argued that the protoplasm (the substance in the cell) was the basis of life, suggesting that it might contain the material governing heredity. With the development of improved lenses and staining techniques in the 1850 s, it became possible to detect structures within the cell. By the late 1880 s, researchers had determined that the nucleus of the cell was the central actor in fertilization; the nucleus was then considered to be the source of idioplasm (the term used by Nägeli for genetic

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[2] Galton introduced the idea of latent and patent elements that both contributed to the structureless elements of heredity. By making information transfer unidirectional, Galton was attempting to rule out Lamarckism (Schwartz 2008).

substance) in the transmission of heritable traits to the progeny. The chromosomes within the nucleus were also identified, and the processes of mitosis and meiosis were described by Flemming and Hertwig, respectively. By the end of the nineteenth century, biologists were occupied with questions of heredity and its relationship to the nucleus and chromosomes. These questions reflect the early interest in the transmission aspect of genetics (Carlson 2004).

Embryology and the study of reproduction are also intimately involved with heredity and transmission. The Aristotelian view of reproduction was that the woman's menstrual blood provided the "raw material" that made up the child and that the man's semen provided necessary "design" through an "animating principle" (Gustavsson 2004). This view was prominent until the seventeenth century when Harvey proposed that eggs were fertilized by the semen, but this theory failed to incorporate the concept of cells. In 1677 Leeuwenhoek first identified spermatozoa and the idea of a material agent of fertilization was born, but it was not until the mid-nineteenth century that Amici first observed the fertilization process of union between egg and sperm. One of the great debates of embryology in the seventeenth and eighteenth centuries was between preformation (i.e., that embryos are essentially "homunculi" [microscopic but fully formed humans] whose growth and development involves only enlargement) and epigenesis (that embryos are constructed from much simpler precursors that develop via some complex mechanism) (Carlson 2004). Improved microscopy would later, of course, support the epigenesist explanation. In the 1890 s, Weismann proposed that meiosis results in a mixing of paternal and maternal heredities in an offspring. He also proposed that reproductive tissue ("germ plasm") is set aside early in development separate from the rest of the body (called the "soma"). Changes in the body (soma) are then not transmitted to the germ plasm according to this theory (Schwartz 2008).

Transmission in the form of breeding of domesticated plants and animals first became the subject of scientific study in the seventeenth and eighteenth centuries. On the basis of his studies of plants, Linnaeus proposed that the "outer" traits of hybrids were derived largely from the male parent, while the "inner" attributes or tissues originated from the female (Carlson 2004). The core "analytical units" examined in these studies were traits or specific characteristics of a species on a phenomenological level; the nature of the relationship between these traits and structures within the body such as the cell were mostly ignored by these scientists. Breeder scientists in the nineteenth century such as Thomas Andrew Knight, Charles Naudin, and even Charles Darwin observed that traits were sometimes passed down to offspring in unexpected ways, but they were unable to explain these observations.

In the second half of the nineteenth century, researchers in biology and heredity sought to answer the following questions: Are all of the characteristics (of a species) controlled by a single, uniform, species-specific substance or is each character determined by a separate particle that can vary independently? Is the genetic material "soft," so that it can change gradually during the lifetime of the individual and/or through generations, or is the genetic material constant and "hard," being changeable only by means of a sudden and radical alternation (later called a mutation)?

How are the particles formed in the body? Do the particles contributed by the parents retain their integrity after fertilization or do they fuse completely? These questions could not be fully answered until the advent of molecular genetics, but they were important questions historically because they centered on the existence of material units of heritability (Mayr 1982).

15.2.2 Classical Genetics

Unlike most of his peers and predecessors, in the late nineteenth century, Gregor Mendel focused on individual physical characteristics ("traits") in the common garden pea. Mendel also applied statistical analysis to the frequencies at which these traits occurred in the offspring from his crosses. Mendel's reductionist approach led to his atomistic model of heredity in which fundamental units of heredity are related to specific binary traits. Mendel proposed that underlying "elemente" are responsible for the production of "merkmal", i.e., physical characteristics of the individual organism (Moore 2001). He did not seek to explain or analyze the nature of this relationship, and he did not apply concepts or results from cytology. The element was an abstract concept connected to specific traits but with no direct association to the physical parts of the organism such as the cell. Mendel's theory provided two crucial contributions to the understanding of genetics: first that some traits are determined by a single factor rather than by many and second that these factors exist in pairs. By proposing the existence of factors in pairs, Mendel was able to explain the results of crosses by the segregation and recombination of these factor pairs. In 1909, Johannsen would name these factors "genes" and the different forms of a gene would later become known as "alleles" (Mayr 1982). The specific combination of these genetic determinants in an individual is its "genotype," and the resulting outward expression of that genotype is the "phenotype." Johannsen was also careful not to claim that the gene is a physical object; instead he regarded it as a hypothetical construct.

The Mendelian "unit-factor" theory of inheritance was ultimately embraced by the scientific community. In Mendelian genetics the genotype was regarded as the phenotype in miniature, not necessarily as a homunculus but rather as a mosaic of heredity particles (whether called gemmules, pangenes, or unit factors), each responsible for a specific component of the phenotype. Each genetic factor was believed to have a one-to-one relationship with the corresponding outward characteristic.

In the early twentieth century, classical genetics emerged as a discipline in its own right when breeding analysis was combined with studies in cytology, embryology, and reproduction. William Bateson was the first to employ the word "genetics" in 1906 to replace the term "heredity and variation" (Carlson 2001). In 1902, Boveri and Sutton proposed that chromosomes are the carriers of the unit factors (genes), that they are transferred to the next generation by gametes, and that configuration of the chromosomes during meiosis explains Mendelian heredity. This chromosomal theory of heredity was questioned until 1911, when Morgan provided the first experimental evidence for it (Morgan 1911). Later Morgan demonstrated that coupling, i.e., the failure of the alleles of certain "linked" genes to assort independently during meiosis, could be explained by the physical proximity to genes to each other on a single chromosome. Linked genes could be separated by a physical breakage-and-exchange process (called "crossing-over") between two chromosomes, but the likelihood of such events was determined by the proximity of the two genes to each other (Schwartz 2008).

Based on the data obtained from extensive linkage studies, Sturtevant constructed the first map of the genes on the X chromosome of *Drosophila* in 1913 (Weiner 1999). This map visualized the spatial relationships of genes to one another on the chromosome, suggesting the representation of the chromosome as a string of beads, each bead representing a different gene (Portin 1993). Accordingly, classical mapping techniques were thereafter commonly used and played an epistemic role in our understanding of the genetic material, representing genes as physical objects more than hypothetic constructs (Gaudillière and Rheinberger 2004; Weber 1998).

During the years after 1940, at the peak of classical genetics, the gene was viewed as an indivisible unit of genetic transmission/function, recombination, and mutation—in Benzer's terms: the cistron, recon, and muton (Benzer 1955). Genetic material was considered to be particulate and to have long-term stability ("hard inheritance"), with mutations representing a discontinuous change to a gene. X-ray-induced mutations were discovered in *Drosophila* by Muller in 1927 and confirmed in maize by Stadler the same year (Carlson 2011). Each gene was assumed to be independent of neighboring genes. Individual traits were the products of genes located at well-defined loci on the chromosomes. Genes were linked to each other on each chromosome but could be separated by crossing-over. Plants and animals were recognized as being "diploid" (for the most part), i.e., the chromosomes in the nuclei of somatic (nonsex) cells exist in pairs (called "homologues"), each member of the pair being derived from the different parents. Homologues are similar in structure and bear the same genes, although they may bear either identical alleles of a gene ("homozygous") or different alleles ("heterozygous").

A strict distinction was made between the genotype and the phenotype. The phenomenon of polygeny (several genes influencing a single trait) and pleiotropy (a single gene affecting several characters) was recognized, thus permitting a much clearer separation between transmission genetics and physiological genetics, i.e., studies of the ways in which hereditary information is manifested during the course of individual development (Mayr 1982). These phenomena conflicted, however, with the accepted model of a one-to-one relationship between genes and traits (Schwartz 2000, p. 28), a fact that created much confusion about this relationship during the classical era. Many geneticists also ignored questions about development in favor of chromosomal mechanics, likely because the latter were more open to a quantitative approach (Lawrence 1992). During the classical era, the most widespread view of the nature of the gene itself (attributable to Weismann among others) was that genes were enzymes, or acted like enzymes, serving as catalysts for chemical processes in the body, producing physical traits (Carlson 1966; Mayr 1982).

In 1948, Boivin and colleagues used chemical analysis to demonstrate that the DNA content of the nuclei in different tissues and organs of individual domestic cows were the same. A year later, Chargaff and colleagues reported that the DNA of calf thymus contained the same proportion of the four nitrogenous bases as did that from the spleen. These findings established the species-specific character of the base composition of DNA. In 1950, Chargaff realized that in all of these cases and in every other species so examined, the quantity of guanine was always equal to that of cytosine, and the amount of thymine was similarly always equal to that of adenine (Chargaff 1951).

In the 1940s and 1950s, breeding analysis and the cytology of animals and plants were replaced at the frontier of research by biochemical genetic studies in fungi, bacteria, and viruses. This change of model organism shifted the emphasis in genetics toward function in general and developmental processes in particular, instead of studies of crossing-over and mutation, which characterized the earlier research. Beadle and Ephrussi determined the biochemical pathway for eye color synthesis in fruit flies (Beadle and Ephrussi 1937). Later, Beadle described the biochemical pathways associated with the synthesis of vitamins and demonstrated that these pathways consisted of ordered series of chemical steps, with a single gene controlling each single step in the chain of reactions. In 1941 Beadle and Tatum proposed that each gene controls one enzyme, and subsequently the hypothesis was coined "one gene-one enzyme hypothesis" by their collaborator Norman Horowitz (Beadle and Tatum 1941; Horowitz 1995), which is still considered essentially correct for microbial genes. However, these genetic and biochemical experiments used the conceptual tools of classical genetics and did not explain the nature of the biochemical pathways or the mechanism by which the genetic material affected the phenotype (Carlson 2004).

Although the classical gene concept was constantly questioned during the first half of the twentieth century, in particular by Richard Goldschmidt (Dietrich 2000) as well as *Drosophila* researchers such as Morgan (Morgan 1934), the term retained a central position in theory and research. But Watson and Crick and their descendants would now change the face of genetics forever.

15.2.3 Modern Genetics

In the early 1940s it was not entirely clear whether DNA or protein was the material that carried the hereditary information. Protein was widely favored because of its largely information-bearing capacity, given that it consisted of 21 amino acids compared to the "simple" four nitrogenous base composition of DNA. The question was first essentially answered in 1944 by Avery and colleagues who showed that the cell-free "transforming principle" known to transform pneumococcus bacteria from non-virulence to virulence (a known inherited trait) was composed of DNA alone and was responsible for bacterial transformation (Avery et al. 1944), although some scientists remained skeptical. More scientists were convinced by the 1952 studies of

Hershey and Chase who used differentially radioactively labeled DNA and proteins to study the transmission of genetic information in T2 bacteriophages, demonstrating that it is DNA and not protein that is the genetic material in viruses as well (Hershey and Chase 1952).

Based on these results as well as Chargaff's chemical studies (described above), physiochemical studies, and the crystallographic studies of Wilkins and colleagues and Franklin and Gosling, Watson and Crick first proposed the double-helix model of DNA (Watson and Crick 1953). This model of DNA fulfilled the necessary requirements for the genetic material, namely, auto-replication, specificity, and information content capacity. The long search for the genetic material had ended; genetic transmission now had a straightforward chemical explanation. This model (1) explained the nature of the linearity of genes, (2) suggested a mechanism for the exact replication of genes, (3) explained in chemical terms the nature of mutations, and (4) explained why mutation, recombination, and function are distinct phenomena. Modern molecular genetics had been born. Now the unanswered questions became increasingly physiological, dealing with the function of genes and their role in ontogeny and physiology.

The impact of molecular biology on our understanding of genetic phenomena has been immense. From 1953 there was a clear explanation for the difference between genotype and phenotype, and it was understood that the genotype does not itself enter directly into developmental pathways but simply serves as a set of instructions for producing proteins. The DNA is arranged in three-letter nucleotide codes, named codons, on each DNA strand. A series of codons that together code for an entire polypeptide constitutes the gene in this classical molecular view. The four possible nucleotides can be arranged in 64 different codons that specify 20 amino acids. The gene was found to be "degenerate" (each amino acid is coded for by more than one codon) and "commaless" and to employ a unique start codon and at least one of three stop codons at its terminus. Gene function occurs via the process of transcription in which single-stranded mRNA is copied from the DNA sequence of the gene and thereafter is translated into an amino acid sequence, a polypeptide.

The discovery of the structure of DNA in the 1950s coincided with the birth of the information sciences and the explication key terms, such as "program" and "code" (Mayr 1982). The metaphor of "program" was first coined by Jacob and Monod to encompass the new concept of gene regulation (Keller 2000). However, philosophers of genetics (i.e., Keller 2000) have suggested that the metaphor of the "genetic program" promotes a more deterministic understanding of the gene, i.e., a blueprint that always works in the same way ignoring any other factors.

Benzer's earlier theoretical division of the gene concept into cistron, muton, and recon proved very useful in molecular genetics, and the nomenclature was adapted to the new findings. The cistron was equivalent to a functional gene (a string of DNA), and the muton and the recon were equivalent to a single DNA base pair because a nucleotide is the smallest unit of genetic material that, if altered, can lead to an altered phenotype or be separated from other such units during recombination (Carlson 1991). From this time until about 1970, the gene (cistron), defined by a complementation test[3], was understood as a contiguous stretch of DNA transcribed as one unit into messenger RNA (mRNA), coding for a single polypeptide (Portin 1993).

After 1970, molecular genetic studies of higher eukaryotic organisms identified an increasing number of anomalies inconsistent with the model of the gene as simply a stretch of DNA that produces a polypeptide, suggesting that this definition is deficient in one or more respects. Today these anomalies include split genes, alternative splicing, complex promoters, polyprotein genes, multiple adenylation, enhancers, overlapping genes, DNA editing, imprinting, and trans-splicing[4]. The common theme in these anomalies is that the structural unit of the gene, the stretch of DNA including all the codons, does not coincide completely with the function of the gene, which is to determine the sequence of amino acids in the produced polypeptide. Instead different molecular processes can impact gene function and development, leading to different context-dependent outcomes.

In the 1980s tools to isolate and determine sequences of nucleotides within DNA and to study the arrangements of gene sequences in the genome of any organism become widely available. The invention of polymerase chain reaction (PCR) by Mullis was an especially important milestone in sequencing and cloning DNA segments (Bartlett and Sterling 2003). No longer were amino acid sequences of proteins determined directly. Instead, if the gene that encoded the protein of interest could be identified, molecular biologists could clone the gene, determine the nucleotide sequence, and deduce the amino acid order from the genetic code (Davis 2003). Public databases (e.g., GenBank) of amino acid and nucleotide sequences proliferated. Informational techniques made it possible to store, analyze, and share large amounts of sequence data, and the field of bioinformatics was born. The sequences deposited in these databases were accompanied by annotations of the function, if known, of each gene and its protein. Hence, the functional aspects of genes became the ultimate goal of research.

In the late 1980s further technological advances in DNA sequencing led to the proposal to determine the nucleotide sequence of the entire human genome. The Human Genome Project (HGP) was launched in 1990 by the U.S. Department of Energy and the National Institutes of Health, under the leadership of James Watson. Zwart (2008) identifies three stages of the HGP. The first stage was a period of implementation and development. The second stage began in 1993 with the appointment of Francis Collins as Watson's successor. At this time the sequencing was subdivided into 23 natural subunits (the chromosomes) which were analyzed by a large number of research groups. The year 1998 was a turning point for HGP and

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[3] The cis-trans complementation test is a test used to determine whether two mutations are alleles or not, i.e., whether they are forms of the same or different genes. By this test, two mutations are not alleles, i.e., are in two different genes; the wild type (nonmutant) phenotype (the mutations "complement" each other) results when the two mutations appear in a single chromosome ("cis"; denoted a1a2/++), whereas if the two mutations appear on separate homologues (in "trans"), the mutant phenotype appears.

[4] See, for example, El-Hani (2007), Falk (2010), Fogle (2000), Rosenberg (1985), and Smith and Adkinson (2010).

the beginning of Zwart's third HGP stage. In that year, Craig Venter announced a competing private project funded by the Celera Corporation. By this date, only 4 % of the human genome had been sequenced, but Venter suggested a much faster methodology relying on automation. The so-called whole genome shotgun method would revolutionize sequencing methodology by relying on powerful computers, which slashed the costs for sequencing the genome (Zwart 2008). A fierce competition between the two groups ensued until June 2000 when Collins and Venter cordially appeared together at the now famous press conference at the White House to announce that the sequencing of the human genome was near completion. Finally in 2004 the public consortium published its completed sequence (IHGSC 2004). The success of the HGP required the development of new research approaches, new technologies, and even new disciplines (e.g., bioinformatics). Sequences of many other genomes would follow, today totaling more than 180 organisms (Genome News Network 2012), resulting in a new approach to genetics called "genomics."

Genomics is the study of the entire genomes of species. Unlike genetics per se, it is concerned with both the coding DNA (sequences that result in mRNA and thus proteins) and noncoding regions (often referred to previously as "junk DNA"). Genomics considers the ways different DNA regions interact in order to determine each region's effect on, place in, and response to the entire genome's structure and function within the cellular context, including development and production of the phenotype. In contrast, the investigation of the roles and functions of single genes is the primary focus of molecular biology and genetics. Epistemologically, genomics is often considered to be a paradigm shift in the study of living things, an "informatization" of life (Zwart 2008). On the other hand, as we leave the cell and biochemistry processes of molecular genetics for the more information-based approach of genomics, we must recognize that genomics also constitutes a return to an approach similar to classical genetics in the sense that it creates a black box of abstract knowledge between the genome and the output of the genome similar to that between the gene and the outcome of the genes in classical genetics.

In 2003 the National Human Genome Research Institute (NHGRI) launched the Encyclopedia of DNA Elements (ENCODE) Project whose goal is to build a comprehensive list of the functional elements in the human genome (Bonetta 2008). Already the HGP revealed that humans only have approximately 20,000–25,000 protein-coding genes (IHGSC 2004), which is similar to the number in the mouse. However the number of human proteins can be estimated to about 90,000 (Magen and Ast 2005). One gene clearly did not code or only one protein! More questions were asked than being answered. What makes up for the differences?

Because protein-coding sequences represent only about 1–2 % of the genome, research turned more of its interest to noncoding regions of DNA, which had previously been thought to be unimportant and was known as "junk DNA." ENCODE has since then shown that the majority of the genome is not "junk" but in fact transcribed into RNA. However about 99 % of the DNA does not code for proteins but, nonetheless, is vital in controlling many cellular processes such as development (Pearson 2006). Hence, to the surprise of many, a lot of work of the genome is transacted not only by proteins but also by RNA itself. This research has focused on the importance of epigenetics, the study of heritable changes caused by mechanisms other than change in the sequence of DNA, e.g., DNA methylation (Bonetta 2008). This focus on mechanisms that function above the level of the genome has led to a number of new twenty-first-century "-omics," including metabolomics, glycomics, and transcriptomics, but most especially proteomics—the large-scale study of proteins, particularly their structure and function (Wilkins et al. 1996).

In the genomic era the so-called central dogma of biology, an idea that originates from molecular genetics, is questioned more than ever. The central dogma of biology held that information flow was unidirectional, from the gene (DNA) to mRNA to polypeptide[5] (Crick 1970). But as Davis concludes: "We have, in the genomic era, converged on the idea that causation goes both ways, upward from DNA and downward from cytoplasm and environment . . . Even the distinction between 'genetic' and 'epigenetic' fails to convey this interdependence" (Davis 2003, p. 249).

15.2.4 Philosophical Implications of the Historical Development of the Gene Concept

In the twenty-first century, there no longer exists a single consensus definition of the gene (if such ever existed), although there are some interesting attempts that have been made (see the discussion below). Instead the gene concept has different meanings for different scientists and even for different settings (Stotz et al. 2004). "This entity [the gene] can, and will indeed most often, be endowed with temporary and discontinuous existence, and it will often require a developmental process at its own level of organization for functional expression" (Gayon 2000, p. 82). Contemporary research has largely discarded the idea of a gene as a discrete material unit, focusing instead on the gene as a functional unit. The function of a gene is no longer solely to produce a polypeptide; instead there exist many categories of genes in addition to the standard enzyme-producing genes, such as genes producing structural proteins, regulatory genes, and genes coding for RNA molecules with other functions ("RNAzymes"). Genes are perhaps best understood as one component of a complex network interaction at a variety of levels from the genome to the proteome and beyond. This lack of consensus, simplicity, or clarity in the definition of such a foundational term as the gene reflects how young genetics is as a science and that the discipline is growing exponentially.[6]

As shown by the historical overview above, the story of genetics in the first half of the twenty-first century is the history of the discovery of the gene and the nature of the genetic material. In the second half of the century, scientists sought to

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[5] (allowing for some possible "reverse flow" from RNA to DNA).

[6] For expanded treatments of the historical development of genetics within HPS frameworks, the reader is directed to Burian 2005; Carlson 1966, 2004; Davis 2003; Keller 2005; Portin 1993; and Sapp 2003, as well Burian 2013; Flannery 1997; Gericke and Hagberg 2007; Kampourakis 2013; Mahadeva and Randerson 1985; Smith and Adkinson 2010; and Vigue 1976 in science education.

determine the nature of the gene and how it manifests itself. The philosophical outcome of this history is that the gene is a polysemous concept with multiple, sometimes incoherent meanings (Burian 2005). The epistemological program of classical genetics was genetic reductionism in which the gene was explained or inferred by phenotypic differences unlike in later molecular genetics in which the gene is a constructive rather than a diagnostic entity, responsible for the production of a protein (Sarkar 2002). The consequence of the shift between classical and molecular genetics is "Mendelian genetics as it was formulated at the time, not mention now, cannot be derived from molecular biology" (Hull 2002, p. 166), i.e., it is not possible to reduce the classical gene into the molecular gene because they are conceptually incoherent.

This is a very important fact for genetic educators to know because both concepts are presented in most biology courses, and as Sarkar points out: "the 'molecular gene' came to be routinely conflated with the 'classical gene'" (Sarkar 2002, p.192), resulting in student confusion and/or misunderstanding. This conflation means that the reductionism of classical genetics is transferred to the DNA segment that constitutes the molecular gene, which evokes the phenomenon of genetic determinism.

Genetic determinism is the view that genes completely determine the phenotypes, as implied in common expressions such as "the gene for X" (as, e.g., the gene for long legs or the gene for intelligence). Determinism ignores the influence of environmental factors, which as described above is far from contemporary molecular views of the gene. Almost no expert who talks about a "gene for" a phenotypic trait literally means what he or she is saying, but this is a common conversational shortcut used by scientists (Falk 2012). It has also been argued that the use of gene metaphors such as "program," "code," and "blueprint" also implies a deterministic understanding of the molecular gene (Keller 2000). Genetic determinism has been shown to be a very persuasive misconception outside the scientific community (Barnes and Dupré 2008; Kaplan and Rogers 2003; Lewontin et al. 1984; Nelkin and Lindee 1995) and is therefore an important concept for educators to be familiar with and to strive to avoid.

In the early years of molecular genetics, the proteins produced by the genes were believed literally to possess the function of the gene, but as has been discovered in the genomics era, individual molecules do not possess complex functions. Complex processes cannot be explained by macromolecules alone (Morange 2002). Functions of organisms are generated at higher levels of organization by regulatory processes in which the proteins, which are produced from the genes, are active components. The molecular components are organized in pathways, networks, and complexes (Morange 2002); therefore, it is typically impossible to predict function or phenotype from individual elementary components (genes or proteins), which is a reductionist view.

The history of genetics also reflects one of the main problems in biology, namely, the relationship between substance and function or structure and process (Burian 2005; Hoffmeyer 1988). In the classical period of genetic history, the gene was a unit of function with no corresponding structure. From 1953 onwards the material structure of the gene (a string of DNA) coincided with function, but as the development of genomics in the last decades, the simple structure of the one-gene-one-enzyme gene has once again vaporized. The post-genomic gene addresses the ongoing project of understanding how gene/genome structure supports gene/genome function (Griffiths and Stotz 2006).

Falk (in Griffiths 2002) has proposed four different potential approaches for dealing with the conceptual difficulties associated with the molecular gene: (1) Abstract away the complexities of molecular biology and define genes in terms of some role they play in evolution. (2) Continue to seek a structural definition at the molecular level (a quest Falk regards as hopeless). (3) Look for a functional account of the gene in molecular developmental biology, relying on a broadening focus from the DNA alone to the wider developmental system in which the concept of the gene is embedded, also denoted as the "process molecular gene concept" (Meyer et al. 2011). (4) Treat genes as "generic operational entities" defined by experimentalists to suit changing needs in different contexts. Kitcher (1982) argues that the clearest explanation of any given phenomenon can only be achieved by adopting different definitions of the gene for different purposes. This is a view that many researchers within HPS agree upon (Burian 2005; Carlson 1991; Fogle 1990; Portin 1993; Waters 1994). As Burian puts it: "There are large and important subcommunities with legitimately different interests – interests that lead them to deal with legitimately different phenotypes" (Burian 2005, p. 142).

Moss (2003) offers another solution to the problem by using two different gene concepts separating the two primary functions, which he terms gene-P and gene-D. Gene-P amounts to the gene as a determinant of phenotypic differences—a notion close to the classical gene but not identical according to Moss because molecular entities can also be used as gene-P. Gene-D in turn corresponds to a real entity defined by some molecular sequence that could be used as a developmental source (Moss 2003). The ENCODE project (Gerstein et al. 2007) defines the gene as "a union of genomic sequences encoding a coherent set of potentially overlapping functional products" (Gerstein et al. 2007, p. 677). Many scientists and philosophers promote this "systemic" or "process" definition of the gene, which emphasizes the view that the whole as well as all the separate parts of an organism must be considered to explain function and phenotype (Keller 2005; Portin 2009).

Keller and Harel (2007) take the implications of the polysemous gene concept a step further, suggesting that the gene concept should be abandoned for a new concept which they termed genetic "functor" or "genitor." A similar strategy is also advocated by Scherrer and Jost (2007) who recognize mRNA as the elementary counterpart of biological function and proposed the term "genon" as the program associated to a specific gene at the mRNA level, given that only mRNA gives rise to one specific protein. Stadler and colleagues (2009) added to this proposed genetic vocabulary, proposing the "genomic footprint," i.e., the fragments of DNA from which the functional sequence is assembled during the expression process.

The different gene concepts and if and how it is possible to link them are one of the central issues in the philosophy of biology[7] but with few exceptions have not been addressed by science education research. Questions about how to define the gene have not yet reached the introductory genetics classroom and have only begun to reach the genetics pedagogy literature. Given the centrality of the gene concept and the lack of a unified and universally applicable and accepted definition of the term the question is: What to teach and what not to teach—how to deal with "the bewildering gene" (as coined by Falk 1986)? How should teachers define and describe the gene for students? And what parts of the historical path that has led to the current state of affairs should be taught—and at what levels? At what level would it be appropriate to address this issue explicitly? What understandings are required for genetic literacy in modern society? How should these HPS issues be reflected in standards documents? What understandings are needed for citizens in the twenty-first century? Although we will return to these issues below, these questions, like the definition of the gene itself, remain largely unsettled by the science and science education communities.

15.3 Contributions of the History and Philosophy of Science to Genetics Teaching and Learning

The previous section provided an overview of the history of genetics and the philosophical implications this development has had on the concept of the gene. This history provides a context for the present section in which we discuss how employing HPS concepts has contributed to teaching and learning in science education scholarship.

Matthews (1994/2014) proposed that HPS can contribute to science teaching and learning in five ways. HPS can:

- Contribute to the fuller understanding of subject matter
- Help teachers appreciate the learning difficulties encountered by students
- Assist in developing a more authentic understanding of science and thus enhance understanding of the nature of science
- Humanize the sciences and connect them to personal, ethical, cultural, and political concerns
- Make classrooms more challenging, by enhancing reasoning and critical thinking skills

These contributions typically overlap and are not meant to be mutually exclusive, but they provide a useful rubric for a review of the field. Using this rubric, the following sections review and critique pedagogical and related scholarship related to genetics, focusing on specific ways HPS can contribute to teaching

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[7] See, for example, Ayala and Arp (2010), Beuerton and colleagues (2000), Burian (2005), and van Regenmortel and Hull (2002).

and learning genetics. How has this scholarship addressed genetics instruction? What HPS-related avenues have been fruitful and in what ways? What HPS assumptions or other issues have gone unexamined or been inadequately addressed? What guidance does this analysis provide for future directions in HPS scholarship related to genetics?

15.3.1 HPS Contributions to Promoting Student Comprehension of Genetics and to Understanding Learning Difficulties in Genetics

In this subsection we combine the first two types of contribution identified by Matthews, given that learning difficulties and the learning of subject matter are often addressed in the same studies. The largest part of genetics education scholarship has clearly focused on enhancing student understanding of subject matter. This work often identifies an assortment of alternative conceptions across ages and cultures as well.

As mentioned above, genetics has long been recognized as one of the most difficult of the biological subdisciplines for teachers to teach and for students to learn. Therefore, we begin by identifying student learning difficulties. Knippels (2002) has reviewed the literature and identified five domain-specific difficulties involved for genetic educators to address:

1. Domain-specific vocabulary and terminology
2. The mathematical content of genetic tasks
3. The cytological processes of cell division, mainly relating to chromosome structure and the associated processes
4. The abstract nature of genetics, due in large part to the order of topics presented in the biology curriculum, which generally separate meiosis from genetics
5. The complex nature of genetics: a macro–micro problem related to how to understand concepts and processes from different systematic levels and their relationships

Alternatively, Tibell and Rundgren (2010) highlight content, reasoning difficulties, and communication issues in "molecular life science" (including genetics). They particularly highlight the issue of domain-specific language and use of visualizations. Other studies of genetic learning have demonstrated the tendency of students to:

- View genetics as a set of rules and patterns of inheritance to memorize more than focusing on understanding genetic concepts and processes in a meaningful way (Lewis and Kattmann 2004)
- Use oversimplified causal explanations instead of biochemical terms or processes (Lewis et al. 2000a, b; Lewis and Kattmann 2004; Marbach-Ad 2001)
- Have difficulty relating structures and concepts to the correct biological organization level and making extrapolations between levels (Duncan and Reiser 2007;

Halldén 1990; Johnstone and Mahmoud 1980; Knippels 2002; Lewis et al. 2000b; Marbach-Ad and Stavy 2000)
- Employ explanations at the phenomenological (i.e., macro level) and/or cellular organizational level, not at the molecular level (Marbach-Ad and Stavy 2000)
- Fail to consider the environmental influences on characteristics (Forissier and Clément 2003)
- Have difficulty relating genetic concepts to each other (Gericke and Wahlberg 2013; Lewis et al. 2000a; Marbach-Ad 2001)

The need for students to be able to integrate concepts and biochemical processes derived from molecular genetics with those from classical genetics has been recognized by many science educators[8]. Hence our conclusion is that much of the literature about students' conceptual understanding of genetics mirrors the dichotomy of classical genetics and molecular genetics (and more recently genomics). It seems that students embrace deterministic classical explanations and tend to reduce classical genetics into molecular genetics, as might be expected from a HPS perspective. Students do indeed have difficulties distinguishing between classical and molecular genetics in genetic texts (Gericke et al. 2013), and they often introduce concepts from classical genetics when reasoning about molecular genetics (Gericke and Wahlberg 2013). The dichotomy between classical and molecular genetics seems to be an epistemological obstacle for learning genetics.

Allchin (2000) adds that the dominance concept is problematic because this concept stems from classical genetics and has no direct correlation in molecular or cellular terms biology. Mendel referred only to traits as dominant or recessive, but now the term is commonly applied to traits, genes, alleles, and even single nucleotide polymorphisms (SNPs). As a result, Allchin (2000) claims that two misconceptions typically emerge in students' minds. First, dominance may be conceived as a form of gene regulation, but there is no general mechanism for dominance in molecular terms. Second, others conceive dominance and recessiveness as the presence or absence of a trait, protein, or gene product, i.e., one sees the phenotype as switch on or off (Lewin 2000). This is correct for some cases but misleading as a general model according to Allchin (2000). It is also important to note that students could confuse the technical meaning of "dominance" with the vernacular meaning, such that "dominance" is conceived as a physical phenomenon involving struggle and power imbalance (Allchin 2000).

Several of the most challenging genetic concepts identified point to ontological difficulties. Among these are:

- Distinguishing between alleles and genes (Lewis et al. 2000a; Pashley 1994; Wood-Robinson 1994)

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[8] See, for example, Duncan and Reiser (2007), Lewis and Kattmann (2004), Lewis and colleagues (2000a), Marbach-Ad (2001), Martinez-Gracia and colleagues (2006), Smith and Williams (2007), Venville and Treagust (1998), and Venville and colleagues (2005).

- Distinguishing between genes and genetic information (Lewis and Wood-Robinson 2000) or traits—leading to difficulties in understanding gene expression (Lewis and Kattmann 2004; Venville et al. 2005)
- Distinguishing between genotype and phenotype (Lewis and Kattmann 2004; Marbach-Ad 2001; Marbach-Ad and Stavy 2000; Venville et al. 2005)

In addition, conceptual change theory (Posner et al. 1982) recognizes that students typically come to the classroom with various understandings and misunderstandings (typically identified as "misconceptions," "alternative conceptions," "commonsense understandings," "naïve conceptions," etc.) that are likely to act as barriers to the development of a more sophisticated understanding of genetics. Studies to identify genetic misconceptions (and to distinguish them from appropriate conceptions) have included a wide range of subjects from elementary school students to teachers, university students, and expert geneticists[9]. For example, Dikmenli and colleagues (2011) found that science student teachers in Turkey had a global understanding of the gene in line with classical genetics (see above) and lacked a modern view of genetics, as did a sample of Moroccan university students (Boujemaa et al. 2010). Both the learning difficulties addressed above and the misconceptions held by students and teachers appear to be similar, although the frequency of learning difficulties and specific misconceptions typically decreases with expertise. Some naïve conceptions are clearly related to development (Venville et al. 2005). Specific misconceptions can often be related to a set of underlying and partially overlapping mental models of the gene (as summarized in Gericke 2008). Genes can be seen as:

- Inherited particles transferred from one generation to the next (Duncan and Reiser 2007; Lewis and Kattmann 2004; Smith and Williams 2007; Venville and Treagust 1998)
- The sole determinants of characteristics (Lewis and Kattmann 2004; Marbach-Ad 2001)
- Objects with inherent actions, i.e., the gene is thought of as a physical object that takes action in an unalterable way in the organism (Martins and Ogborn 1997)
- Sets of commands that control characteristics (Martins and Ogborn 1997; Venville and Treagust 1998)
- Active particles that also control characteristics (Duncan and Reiser 2007; Venville and Treagust 1998)
- Biochemical sequences of instructions connecting genes and protein synthesis, and protein synthesis and phenotype (Venville and Treagust 1998)

Genetic misconceptions are very common. In a recent analysis of 500 essays submitted by high school students in a contest sponsored by several professional societies, 56 % were judged to have some "major" misconception (Shaw et al.

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[9] See, for example, Abrams and colleagues (2001), Donovan and Venville (2012), Lewis and Kattmann (2004), Marbach-Ad (2001), Shaw and colleagues (2008), Venville and Donovan (2005), Williams and Smith (2010), and Wood-Robinson (1994).

2008). The most frequently reported view seems to be that genes are considered to be physical particles and/or the sole determinants of phenotypic traits (as in "the gene FOR sickle cell anemia"), ignoring epigenetics—the fact that other components of the genome, cell, and environment impact phenotype as well (Lewis 2012). Deterministic views of genes are common—even among teachers (Castéra and Clément 2012) and can be problematic in a variety of ways, including especially in making decisions about personalized genetic testing and the interpretation of such tests (Bartol 2012). Likewise, making a link between genes and protein synthesis is rare among many students. Hence naïve understandings of genetics can be characterized as typical of the historical classical view (Gericke and Hagberg 2007).

The central question in the present context is: To what extent is the design of genetics instruction informed by HPS concepts? Surprisingly, the answer is that HPS concepts have not been used very widely to inform genetics pedagogy directly. The most frequent use of HPS concepts has been to argue for the importance of including genetic history and historical models in instruction. For example, Kinnear (1991) argued over 20 years ago for the use of historical genetics models as an important tool in teaching genetics:

> A valuable experience for students is to explore the development of a concept or model over time, and to note its maturation from initial observation, through descriptive statements, and finally to an explanatory model with predictive power that is generally accepted by the relevant community of scholars. (Kinnear 1991, p. 71)

The experience of tracing the development of an explanatory model could clarify students' own understanding of the concepts involved, particularly when several rival models exist. In addition, historical perspectives can sensitize students to the development of historical models, the constraints imposed on a model by its underlying assumptions, and the effects of scientific methodology. A historical approach can challenge the view that the "right" model exists and is waiting to be "discovered" like an archaeological artifact. A historical approach can also help students recognize that explanatory models are constructs developed over time for specific purposes and that they can be flawed or inadequate in a variety of ways (Kinnear 1991).

Gericke and Hagberg (2007, 2010a, b) also argued for the use of historical models as a tool for improving genetics teaching. Gericke and Hagberg described and categorized five historical models of the gene and its function. Conceptual consistency problems between the historical models were identified and compared to areas of genetics in which identified learning difficulties are reported. Extensive parallelism was observed, suggesting that learning might be enhanced by learning about the history involved in the development of the genetic models and reasons to why each was supplanted by subsequent models. A similar teaching strategy has also been suggested by Othman (2008). Smith and Adkinson (2010) have suggested a revision of the historical models of Gericke and Hagberg into an integrated model that takes into account concepts from genomics resulting from the ENCODE project, such as single nucleotide polymorphisms (SNPS) and transcriptionally active RNAs (TARs). In a recent paper by Meyer at al. (2011), they review different definitions of the gene (see Sect. 15.2.4) and make a suggestion to which school level different views of genes could be introduced (Meyer et al. 2011; see Table 1, pp. 25–26).

Several researchers employ instructional designs that encompass both historical and nature-of-science (NOS) approaches. These include Clough, Stewart, and colleagues who will be addressed in the following section of this chapter.

Perhaps the most explicit example of the use of HPS concepts in the design of genetics pedagogy is the work of Venville and colleagues (2005) who used both "ontological and epistemological lenses" so as to identify barriers to learning genetics within interview data from 6- to 10-year-old Australian children. Ontology was referred to understanding which entities belong with others in biological categories (e.g., living vs. nonliving things) and understanding the distinction between different entities (e.g., genes should not be seen as the same as the traits they determine, a situation that would support deterministic views of the gene—i.e., the allele for black hair color would itself be colored black). Epistemology referred to the structure of the students' knowledge, which was reported as piecemeal and disconnected. Dougherty (2009) also argues that the predominant historically based mode of genetics instruction "primes" students to hold deterministic views.

Somewhat less directly, Duncan and colleagues (2009) used the framework of learning progression to develop a sequence for teaching modern genetics from grades 5–10, based in particular on the work of Stewart and colleagues (see next section) and Venville and colleagues (see throughout this chapter) but to a lesser extent on HPS. Duncan and colleagues identified three key aspects necessary in effective genetics instruction: (1) the big ideas in modern genetics and the knowledge and abilities that students should master by the end of compulsory education, (2) the progression of learning that students are expected to make over several grades, and (3) the identification of learning performances and development of assessments for the proposed progression (Duncan et al. 2009). This approach has recently been shown to be effective in field testing (Duncan and Tseng 2011; Freidenreich et al. 2011). Another learning progression has been suggested by Roseman and colleagues (2006) based on strand maps that are based on the logic of the discipline and existing learning research (Project 2061 Atlas of Science Literacy; AAAS 2001).

Dougherty and colleagues (2011) shift our concern to the need to improve national and state standards with regards to genetics. In a study of standards in all 50 US states, Dougherty and colleagues found that 85 % of the standards were inadequate. The standards in virtually every state failed to keep pace with changes in the discipline as it has become genomic in scope, omitting concepts related to genetic complexity, the importance of environment to phenotypic variation, differential gene expression, and the difference between inherited and somatic diseases (Dougherty et al. 2011).

Other research groups have also proposed sets of recommendations for effective genetics instruction. Venville and Treagust (2002) recommend the following:

1. Use of appropriate, extended analogies and models
2. Move beyond Mendel

3. Link between concepts
4. Emphasize levels of representation (p. 20)

Many authors have also addressed the “macro–micro” problem of understanding genetic concepts that require understanding phenomena at multiple levels of organization (e.g., Duncan 2007; Johnstone and Mahmoud 1980; Knippels 2002; Schönborn and Bögeholz 2009; Van Mil et al. 2013). To address this learning difficulty, Knippels (2002) has developed “yo-yo learning,” a specific teaching design that explicitly asks students to move up and down different organizational levels of biology, from molecular to cellular to the individual level in order to explain genetic phenomena. The students in her study improved their ability to interrelate different organizational levels and properly relate genetic concepts to the different levels (Knippels 2002). Knippels also recommends that genetics instruction should focus primarily on linkage of concepts and levels of representation (Knippels et al. 2005):

1. Linking the levels of organism, cell, and molecule
2. Explicitly connecting meiosis and inheritance
3. Distinguishing the somatic germ cell line in the context of the life cycle
4. An active exploration of the relations between the levels of organization (p. 108)

The work from Knippels and colleagues (2005) has been extended by the Dutch group at Utrecht University. Verhoeff and colleagues (2009) suggest system thinking (linked to systems biology), as a possible way to integrate genomics into biology curricula. System thinking is a holistic approach that employs an iterative process of data gathering and data modeling (Verhoeff et al. 2009). Voerhoeff and colleagues (2008) defined four elements of system thinking in biology education: (I) being able to distinguish between different levels of organization, (II) being able to interrelate concepts at a specific level of organization, (III) being able to link biology concepts from different levels of organization, and (IV) being able to think back and forth between abstract visualizations (models) to real biological phenomena. This approach also suggests a learning progression.

Three other models for designing genetics curricula have been proposed in the literature (Dougherty 2009; Elrod and Somerville 2007; Hott et al. 2002). Dougherty calls for “inverting the curriculum,” beginning with presentation of common qualitative traits instead of simple Mendelian (“monogenic”) traits to address the common student misperceptions that most human traits follow the latter, not the former pattern, and that environment has little if any effect on final phenotypes. Dougherty argues that this approach better prepares students for becoming wise medical consumers “in a world where personalized medicine will rely increasingly on genetic testing, risk assessment, predispositions, and ranges of treatment options” (Dougherty 2009, p. 8). Elrod and Sommerville’s curriculum (for upper-level biology majors) employs student identification of original literature to address student-generated genetics research questions, focusing on developing student competence in information gathering, interpretation, and integration as well as genetics and the NOS. A paper from Hott and colleagues (2002) report of the “Information and Education

Committee of the American Society of Human Genetics" that presents an unordered list of genetics topics and subtopics for medical school curricula. None of these approaches is explicitly informed by HPS concepts.

The use of HPS as an analytical tool for examining textbooks has been a fruitful area of research. Hurd (1978) investigated the historical and philosophical treatment of genetics in 128 US school and college textbooks published between 1907 and 1977. Hurd concludes that the textbooks did not provide a basic understanding of human genetics. Blank (1988) showed how uncertain genetic mechanisms are often presented as dogmatic facts in textbooks. The conceptual content of textbooks has been analyzed in several countries. A genetic deterministic approach to genetics, ignoring environmental interactions, was found in French and Tunisian secondary level biology textbooks (Abrougui and Clément 1997; Forissier and Clément 2003; Castéra et al. 2008a, b). Moreover, the tendency of using an implicit genetic deterministic ideology in textbooks was found in a study of 16 countries, although the degree varied between different countries (Castéra et al. 2008b). Martinez-Gracia and colleagues (2006) found that Spanish high school biology textbooks describe many procedural details of molecular genetics, but these do not facilitate understanding of the main ideas and concepts. A similar lack of integration was also found in an evaluation of US high school biology textbooks (AAAS 2008). Information about the molecular basis of heredity in typical textbooks was presented in a piecemeal fashion. DNA and other biochemical molecules were described in great detail, as were various biochemical processes of gene function. Changes in genes and their consequences, however, were described in later chapters. The authors of both the Spanish and US studies advocate the incorporation of Mendelian concepts into molecular genetics. The use of different historical genetic concepts within textbooks has been reported in Brazil (El Hani et al. 2007; Santos et al. 2012) as well as from Sweden and several English-speaking countries (Flodin 2009; Gericke and Hagberg 2010a, b) indicating a frequent use of hybrid models, i.e., incorporating aspects of different historical views. A more modern idea about the gene seems to be absent in most textbooks (Gericke and Hagberg 2010a, b; dos Santos et al. 2012). In a recent comparative study of textbooks from six counties, Gericke and colleagues (2012) identified a common gene discourse in which ontological aspects of the academic disciplines of genetics and molecular biology were found but without their epistemological underpinnings. Different models and concepts from both classical and molecular biology were used interchangeably in a nonhistorical fashion. Also in the reviewed texts the most frequent explanatory models and concepts of the gene were those that promote a deterministic notion of the gene. An in-depth survey and analysis of textbook research in genetics is provided in the next chapter of this book by El-Hani. An interesting analysis of the use of different historical genetic concepts in school would be to use the Didactic Transposition Delay framework introduced by Quessada and Clément (2006). The framework refers to the time elapsed between appearance of a scientific concept in professional literature until it appears in school syllabi.

Alternative conceptions have also been an informative lens for designing conceptual change style genetics teaching. For example, in a study of instruction about gene technology (Franke and Bogner 2011a, b), one group of 10th graders was confronted with alternative conceptions to central issues of the topic while the control group was not. Compared to controls, experimental students abandoned more of alternative conceptions in favor of a scientific view. These students also showed either the same or greater cognitive achievements compared to controls, although previous study has shown that radical conceptual change in ontological conceptions of the gene remains a difficult challenge (Tsui and Treagust 2004b).

Venville and Donovan (2005) surveyed genetic experts about their views of the gene concept and the key concepts that students should learn in genetics. These experts commonly pointed out four themes of importance that should be addressed in teaching: (1) "Genes are regions of DNA that are a code for making polypeptides," (2) "genetic determinism is a myth," (3) "the importance of the impact of the environment on the phenotype," and (4) "genetic control and gene expression" (Venville and Donovan 2005, p. 22). Burian (2013) make three principal claims that should guide genetics instruction: "(1) Questions about genes often yield different answers about what a gene is, or is like, or how it acts" (i.e., the polysemous gene concept as discussed in Sect. 15.2). (2) The resolution of such conflicts often requires new technologies (see the historical overview in Sect. 15.2). (3) The dispute of what genes are "reinforce[s] the centrality of the tension between accounts of gene structure and gene function" (Burian 2013, p. 341). Hence, the issues identified by both Burian (2013) and Venville and Donovan (2005) as central for genetics instruction are some of the main themes of the history and philosophy of genetics described in the first section of this chapter. Burian also advocates for a teaching approach that connects conceptual understanding with the understanding of the nature of science, pointing out the importance of including the discovery process of science in genetics instruction (see Sect. 15.3.2 for further discussion).

Another tactic for teaching about the gene is suggested by parallels with Smith's approach to defining the term science (Smith and Scharmann 2006), based on the work of Wittgenstein (1953/2001) and Kuhn (1974). Analyzing the concept of "games" as an example, Wittgenstein pointed out the difficulty of explicitly defining polysemous concepts. (Think for example about a definition that would include solitaire, chess, and the children's game of "duck, duck, goose.") Kuhn argued that, in practice, people come to understand the term "games," i.e., by ostension, by experience with examples, and by counterexamples of the term, not from a list of necessary and sufficient conditions. Wittgenstein does not argue that it is impossible to define "games" but that an explicit definition is not needed because we can use the word successfully without it. The focus of instruction, therefore, should be on learning to use the term more than to define it. It may thus be most effective to begin instruction with only a broad working definition of genes or perhaps "case studies" of specific genetic disorders as suggested by Duncan (2007) and Mysliwiec (2003), followed by consideration of a number of prototypical genes (and different uses of the term), each of which focuses on different meanings, functions, exceptions, etc.

These are important issues that need to be addressed immediately. These recommendations need to be tested experimentally. Furthermore, it seems likely that using an HPS lens would be a fruitful approach to designing pedagogical experiments to answer such questions.

15.3.2 HPS Contributions to Enhancing Understanding of the Nature of Science (NOS)

Separating HPS contributions to genetics understanding and NOS understanding is difficult—perhaps impossible—because the majority of science education scholarship focusing on teaching the NOS (i.e., science as a way of knowing; the epistemology of science [Lederman 1992]) has been within a disciplinary context, primarily in evolution instruction. Some genetics education researchers have advocated focusing genetics instruction on enhancing NOS understanding as well (e.g., Allchin 2003; Gericke and Hagberg 2007; Kampourakis 2013). As in the preceding section, instruction about the history of genetics plays a central role in much of this work. Kampourakis claims that: "in order to provide a more accurate depiction of science, it is necessary that historical details are taken into account and that teachers, science educators, and textbook writers provide a more actual historical description and a more accurate depiction of the nature of science" (Kampourakis 2013, p. 320).

Clough and colleagues (Clough and Olson 2004; Metz et al. 2007) have produced a number of excellent historical narratives of the history of genetics that aim to increase students understanding of NOS. Clough and colleagues propose using these stories in an instructional design that interrupts the story at certain points, brings the student "alongside the scientists," and requires students to manipulate ideas and try to solve the problems that concerned the scientist, drawing inferences, making predictions, etc. One of these activities involves the story of Mendel and another focuses on the story of Watson, Chargaff, the nature of the genetic material, the pairing rules, etc. (see Sect. 15.2 for the historical background). These activities are focused on student understanding of the NOS. Although stories about scientists and their work appear to be inherently motivating, Allchin (2003) argues for a cautious use of historical narratives in science instruction because they are commonly used to give a misleading understanding of the NOS, resulting in "scientific myth conceptions." Allchin notes that historical reconstruction often describes scientific discovery as a heroic event following certain narrative patterns. Typically, these patterns are historically inaccurate and follow the architecture of myth, which misleads students about the NOS. Allchin notes that the story of Mendel as presented in genetics instruction typically includes several common ingredients of myth: monumentality, idealization, affective drama, and explanatory and justificatory narrative. Allchin argues for a different type of history that conveys the NOS more effectively.

Lin and colleagues (2010) designed a genetics unit for grade 7 Taiwanese students using a "historical episodes map (HEM)" comprised of 20 historical episodes and four storylines in the development of genetics from early times to the rediscovery of Mendel's work. Compared to control students who received instruction based on the textbook alone, students in the experimental group evidenced greater understanding of the NOS (ES = 0.24) and more positive attitudes toward science (ES = 0.14). Understanding of genetics was not measured. Similar methodology and gains in

NOS understanding were also reported by Kim and Irving (2010) for US high school biology students.

For college non-biology majors and courses in the history of genetics (but not for high school biology), Burian (2013) argues for a teaching approach that uses the processes of discovery, correction, and validation by utilizing illustrative episodes from the history of genetics. This approach concentrates on understanding "the processes of investigation and the fundamental issues that are posed by genetic sciences" (Burian 2013, p. 326) as a means to achieve three of Matthew's goals—to increase conceptual understanding, enhance NOS understanding, and humanize the discipline. These are promising results, and these instructional methods deserve further study.

In the high school biology curriculum designed by Cartier and Stewart (2000), students work in groups structured like scientific communities to build, revise, and defend explanatory models of inheritance phenomena, with the aim of improving both genetics and NOS understanding (see also Cartier et al. 2006). Open problem-solving has also been reported to promote a change in the students' view of the NOS, which was not found in the control group in which problem-solving was not used (Ibáñez-Orcajo and Martínez-Aznar 2007). Yarden and colleagues have also designed a promising web-based genetics program that employs students using an authentic sequencing tool to identify a gene within a hypothetical narrative story context (Gelbart and Yarden 2006, 2011; Gelbart et al. 2009; Stolarsky et al. 2009). Qualitative analysis of this instruction suggests that the instruction "promotes construction of new knowledge structures and influences students' acquisition of a deeper and multidimensional understanding of the genetics domain" (Gelbart and Yarden 2006; p. 107). No quantitative analyses were reported and are clearly called for. Lederman and colleagues (2012) have proposed a set of modern genetic applications (genetically modified foods, genetic testing, and stem cell research) that raise many socio-scientific issues (to be addressed below) and have given suggestions about how these might be used to also promote NOS understanding.

The historical reconstruction of genetics research also raises the issue of the temporal relationship between evolution and genetics and the order in which the two should be taught. Some educators have made the case that instruction is likely to be more effective if genetics is presented first as a basis on which to build an understanding of evolution, thus avoiding the difficulties encountered by Darwin (see Sect. 15.2.1). This approach follows the basic assumption of most curriculum design that simpler concepts should be presented before they are built together into more complex concepts, i.e., that understanding genetics first helps students subsequently understand how evolution operates, employing genetics concepts. Bizzo and El-Hani (2009) argue that the claim that understanding genetics is necessary to understanding evolution is "wrong from an historical and an epistemological perspective" (Bizzo and El-Hani 2009, p. 113), although they do not claim that the opposite sequence is more "efficient" (effective?). Their primary argument is that teaching evolution first, noting that Darwin held "a 'right' model of evolution while having a 'wrong' model for heredity" (p. 113), provides students with the more appropriate "image of science [recognizing that scientists have] all sorts of ideas, including some that proved to be wrong" (p. 113). The question of the proper instructional sequence of evolution and genetics is clearly central to biology education and more studies are called for. Evolution has been placed at the end of the curriculum for many years, but student understanding of both topics has been less than optimal, although student gains are likely affected by a host of other factors, not the least of which is that evolution in many countries is often not taught either because it is controversial or because the semester ends before teachers get to the last chapter in the text. The "best" sequence may even depend on the instructional goals—genetics understanding, evolution understanding, NOS understanding, or some combination of the three. Surprising as it may seem, the question remains open as a major gap in genetics pedagogy; direct experimental comparison studies are clearly called for.

This review demonstrates that the history of genetics is the most explored aspect of NOS in the literature. Moreover, there seems to be a strong rationale for the use of history in the design of instruction, and research to date that employs variations of this approach is promising. The philosophical and conceptual aspects of genetics, however, have received little or no attention in such design and are likely to be fruitful avenues for future research. Questions that remain to be addressed include the following: What pedagogical models are the most effective for improving genetics understanding? For addressing misconceptions? For enhancing the understanding of NOS? What aspects of the NOS are most suitable to address in genetics instruction? How could NOS targets be addressed in genetic education and then reinforced in subsequent evolution instruction, or vice versa?

15.3.3 HPS Contributions to Humanizing Science to Personal, Ethical, Cultural, and Political Concerns

Perhaps the best example of scholarship that aims to humanize science through genetics instruction is the use of history in the classroom as described in previous sections. Genetics instruction typically follows the historical development of genetics research (Dougherty (2009). Genetics instructors have traditionally used narratives——such as the story of Mendel and his pea experiments, sometimes adding humanizing details (see Sect. 15.3.2).[10] Davis (1993), for example, explains how to include the origins of Punnet square, as well as the studies of Bateson and Punnett that first identified linked genes. Fox (1996) describes a classroom exercise that uses a letter from Max Delbruck to George Beadle to stimulate interest in molecular biology. Simon (2002) includes developments from human gene therapy. Ohly (2002) used the story of Chargaff and the development of the DNA base-pairing rules to show how laboratory routines and their development interact with the underlying theoretical framework and the way of thinking ("denkstil") of a collective of

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[10] See, for example, Allchin (2003), Clough (2009), Clough and Olson (2004), and Metz and colleagues (2007).

researchers. Crouse (2007) describes a method for teaching upper-level undergraduate and graduate students the analysis of X-ray diffraction of DNA through a set of historical steps using the original methods employed by Watson, Crick, Wilkins, Franklin, and Gosling that led to the proposal of the helical structure of DNA.

Both Yarden and colleagues (2001) and Goodney and Long (2003) have developed primary research literature-based developmental biology curricula for high school biology majors. Goodney and Long argue that the success of a scientific revolution, such as the advent of molecular genetics, is due not only to the strength of the ideas but also to the persuasive power of language. They also argue that primary research literatures that start a scientific revolution are understandable for a broad range of readers because their purpose is to speculate, imagine, theorize, and persuade rather than merely inform as in normal science.

Chamany and colleagues (2008) suggest that the social context is important when teaching biology to model social responsibility for biology students as part of biology literacy for non-major students. The authors also give practical examples of the use of this approach in genetic topics such as sickle cell anemia and gene regulation. Venville and Milne (1999) draw on the history of genetics and the lives and scientific accomplishments of female geneticists Nettie Stevens, Rosalind Franklin, and Barbara McClintock to illustrate surprisingly contrasting accounts of events and to focus on the people involved in order to increase the motivation of students (especially females) in learning genetics. Wieder (2006) describes the use of a student-designed play followed by work by proposing a working model of DNA structure for humanizing high school biology and highlighting the people and processes of science (Wieder 2006).

An education tool widely used to humanize science (and more specifically, genetics) and make it more relevant to students is the use of socio-scientific issues (SSI), which is designed to engage students in culturally and socially relevant decision-making, citizenship, argumentation, and ethical reasoning (Blake 1994; Sadler 2011). Available examples in genetics include activities that focus on human cloning and genetic screening (Simonneaux 2002), GMO (Dawson and Venville 2010; Ekborg 2008; Simonneaux 2008), genetic testing (Lindahl 2009; Boerwinkel et al. 2011), and biotechnology (Dawson and Venville 2009; Lewis and Leach 2006; Sadler and Zeidler 2004, 2005). Using web-based approaches for learning genetics in socio-scientific settings has been developed in Norway. Viten[11] is a web-based platform that contains digital teaching programs in science for secondary schools and provides teaching materials relating to gene technology (Furberg and Arnseth 2009; Jorde et al. 2003). Because SSI is closely related to argumentation, more about issues related to argumentation in these studies are outlined in next Sect. 15.3.4.

In 1990 the NIH's National Human Genome Research Institute (NHGRI) committed 5 % of its annual research budget to study Ethical, Legal and Social Implications (ELSI) of the Human Genome Project, and a number of fact sheets, teaching resources, learning tools, and funding opportunities are available at the

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[11] www.viten.no

HGP website[12]. This is a resource that has largely been untapped by the science education research community to date. One example of how ELSI issues might be addressed is an interdisciplinary course (taught by a biologist, a linguist, and an educator) which aimed to increase booth genetics content knowledge and awareness of equity and fairness (Gleason et al. 2010). The American Society of Human Genetics (ASHG) website[13] is also an excellent source of genetics education resources, including instructional modules, books, videos, and websites recommended by their Genetics Education Outreach Network (GEON).

Race and eugenics are another part of the history of genetics that focus on social factors involved in genetics. Eugenics was widely accepted by the scientific and political elite in many countries in the early twentieth century and has often been addressed in the educational literature. Mehta (2000) provides a historical overview of eugenics from ancient Greece to genetic engineering. Rodwell (1997) profiles the history of Caleb Williams Saleeby, a late nineteenth-century propagandist of eugenics, and Greenwald (2009) examines Alexander Graham Bell's role and influence in the American eugenics movement. These materials have promise for classroom use, but Cowan (2008) argues that the common view of the connection between medical genetics and eugenics is historically fallacious. She claims that from the very beginning, the goal of the founders of medical genetics (e.g., Neel, Fuchs, Kaback, Guthrie et al.) was the relief of human suffering not improvement of the race. Anderson (2008) describes efforts in medical education to teach that race no longer is considered a biologically legitimate concept and to demonstrate that race remains an influential social classification, causing social and biological harm. Thus, addressing eugenics in the classroom appears to be fraught with both opportunities and pitfalls.

Humanizing genetics may be a particularly useful approach for reaching students from select genetic subgroups. For example, Gates, the originator of the popular PBS documentary series "African American Lives" (WNET) (see von Zastrow 2009), proposed an interesting "ancestry-based curriculum" based on genealogy and DNA research for African American students. Gates argues that students who "examine their own DNA and family histories [will be more] likely to become more engaged in history and science classes" (von Zastrow 2009, p. 17).

Use of examples of genetic phenomena that are particularly exotic and/or relevant to the students' own families is yet another approach to humanizing genetics. One interesting example is the inheritance of a certain genetic diseases in certain Nigerian families. In this culture inheritance of a particular genetic disorder is commonly explained as the result of curses and extramarital affairs (Mbajiorgu et al. 2007). Similarly, Santos and Bizzo (2005) interviewed 100 adults from within two large Brazilian families in which many members are affected with one of two rare genetic disorders. The prevailing community explanation in this case was that the disorders were an inherited illness in the blood related to contamination by syphilis. The genetic basis of these disorders has immediate relevance to students in these

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[12] www.genome.gov

[13] www.ashg.org/education/resources.shtml

cultures; this work reemphasizes both the importance of a thorough understanding of student preconceptions about the content of instruction and of the great impact of culture and worldviews on learning. Teaching Western science explanations of inheritance in these cultures would certainly humanize the content but, given the prevailing culture, would be challenging indeed. Such work is also typically aligned with pedagogy based on conceptual change theory, the instructional approach taken by Santos and Bizzo. The value of using these examples in Western classrooms would be interesting to investigate as well.

15.3.4 HPS Contributions to Enhancing Reasoning, Argumentation, and Thinking Skills

Genetics instruction provides a fruitful venue for developing student reasoning and thinking skills. As alluded to above, genetics teaching and learning are perennially recognized as challenging, and the cognitive demands of the content are great. The reasoning and thinking skills required for solving classical genetics problems have been widely recognized as a central reason for the difficulty many students experience in this field (e.g., Smith 1983; Mitchell and Lawson 1988; Cavallo 1996). We have also alluded in Sect. 15.3.1 to the high cognitive demands required by working across as many as four levels of organization from the molecular to the ecological (e.g., Knippels 2002; Duncan and Reiser 2007).

Solving sets of typical closed-ended Mendelian genetics problems has long been a central component of introductory genetics teaching and learning. Various aspects of the problem-solving skills required, how the skills employed vary with levels of expertise, and how problem-solving contributes to genetics learning have been investigated in a range of older studies, beginning with the work of the second author of this chapter[14]. More recently Ibáñez-Orcajo and Martínez-Aznar (2005) found that, compared to control subjects, students who solved open-ended genetics problems showed significantly more frequent use of more advanced genetic models—differences that persisted over time (at 5-month posttest). Ibáñez-Orcajo and Martínez-Aznar interpreted these gains as the result of “metacognitive reflection by students that become[s] apparent in conceptual restructuring” (Ibáñez-Orcajo and Martínez-Aznar 2005, p. 1508). The use of open-ended problems for promoting problem-solving and critical thinking skills such as metacognition is a promising avenue for future research.

Both Mitchell and Lawson (1988) and, more recently, Cavallo (1996) have demonstrated the necessity of general developmental reasoning skills for solving genetics problems. Duncan (2007) demonstrated the importance of additional, mid-level, domain-specific heuristics and explanatory schemas for solving problems in

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[14] See, for example, Cavallo (1996), Finkel (1996), Hafner and Culp (1996), Mitchell and Lawson (1988), Smith (1983), Smith and Good (1984), Stewart (1983, 1988), Stewart and van Kirk 1990, and Wynne and colleagues (2001).

molecular genetics in a university genetics course for biology majors. These findings support Duncan's argument that genetics instruction should be focused on "learning of causal mechanisms rather than disconnected details of structures and processes" (Duncan 2007, p. 321). Venville and Donovan (2007) have proposed such a learning program for second graders (ages 6 and 7) in which students made qualitative gains in understanding of causation in heredity.

Understanding and using genetic models can also be an avenue to enhancing thinking and reasoning (Gericke and Hagberg 2007, 2010a, b). Physical manipulative models (e.g., beads, cutouts) have long been a component of teaching genetic phenomena from nuclear division (Lock 1997; Rotbain et al. 2006; Smith and Kindfield 1999) to replication, transcription, and translation and have been shown to enhance learning outcomes (Venville and Donovan 2008). Rotbain and colleagues (2005) also demonstrated the positive learning benefits of an activity in which students drew their own genetic representations, although these gains were less than those of students who participated in computer animation instruction (Marbach-Ad et al. 2008).

Over the past decades, Stewart and his colleagues have developed and tested a very successful genetics course that employs model-based inquiry. The program employs the Genetics Construction Kit software as a context in which high school students build and evaluate their own scientific models to explain genetic phenomena[15]. Stewart and colleagues (2005) suggest that genetics students need to understand and reason on the basis of three models: inheritance pattern models (explaining patterns of inheritance across generations), the meiotic model (explaining chromosome and gene behavior during the generation of gametes), and the biomolecular model (explaining the role of DNA and proteins in bringing about an observable phenotype).

The use of models and modeling as a tool to facilitate learning and reasoning has been employed in several other computer-based and web-based learning environments as well. These include *CATLAB*[16] (Simmons and Lunetta 1993), *GenScope* and its successor *Biologica*[17] involving pea plants and dragons (Buckley et al. 2004; Hickey et al. 2000, 2003; Tsui and Treagust 2003a, b, 2010), *The Virtual Flylab*[18] and *Genetics Construction Kit* (GCK)[19] (Soderberg and Jungck 1994) both involving *Drosophila,* and the "Simple Inheritance" unit of Marcia Linn's *Technology Enhanced Learning in Science* (TELS)[20]. Of these, GCK provides the greatest diversity of uniquely generated problems and is the most widely used (Echevarria

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[15] For more background see the following references: Finkel and Stewart (1994), Hafner and Stewart (1995), Passmore and Stewart (2002), Stewart and colleagues (1992), and Thomson and Stewart (2003).

[16] www.emescience.com/bio-software-catlab.html

[17] www.concord.org/biologica

[18] www.biologylabsonline.com

[19] www.bioquest.org/indexlib.html

[20] http://telscenter.org/curricula/explore

2003; Finkel 1996; Hafner and Stewart 1995). *Avida-Ed*[21] (Holden 2006) and *EVOLVE*[22] both simulate evolution of an artificial life form (Soderberg and Price 2003). Likewise, *WorldMaker,*[23] an iconic modeling program for learning about complex natural and social phenomena, has been used to teach genetics (Law and Lee 2004). GCK has been modified into the *Virtual Genetics Lab*[24] (VGL), an open-source simulation that is freely available on the Internet. Solving the problems generated by these simulation programs is generally recognized to promote motivation, and deep conceptual understanding of genetics and advanced reasoning skills (e.g., Tsui and Treagust 2003a, 2004a). Somewhat more broadly, web-based tools such as virtual chatting have also been shown to be useful in teaching model-based reasoning in genetics (Pata and Sarapuu 2006).

The use of metaphors, analogies, and analogical reasoning, a widely used instructional strategy in science (Brown and Clement 1989), has been employed in a limited number of genetics instruction studies. In an experimental collage genetic course, for example, instruction that involved complex analogies resulted in significantly higher student achievement compared to controls (Baker and Lawson 2001), although the use of analogies did not obviate the need for higher-order reasoning skills.

Instructional metaphors and analogies, however, have both strengths and weaknesses. Venville and Donovan (2006) argue that the widely used analogy of genes as small entities in the nucleus of cells that play an important role in inheritance, development, and function is the most productive way of promoting genes in school science. By definition, however, metaphors and analogies oversimplify the target phenomenon and thus can lead to misconceptions. The shortcomings of the particulate “beads-on-a-string” model of genes, for example, have been addressed at length earlier in this chapter. Another common metaphor is that the gene is the “blueprint of life” (Tudge 1993), but this metaphor is “potentially a misleading myth because genes are not passive bystanders” in the cell (Venville and Donovan 2006, p. 21). Likewise, the blueprint metaphor suggests that the genetic plan is static and unchanging and that there is a one-way flow of information (p. 21). These authors prefer the analogy of genes as “recipes” with transcription factors as “chefs” that decide which recipe to make. “Chefs” and “recipes” need each other to function, a much less deterministic metaphor (Venville and Donovan 2006).

Teachers are also often unwisely using anthropomorphic metaphors and language, which can contribute to student misconceptions (Venville and Donovan 2006). Anthropomorphic metaphors such as “genes for long legs” or “genes for cancer” are convenient figure of speech and much in line with the old unit factor theory of Mendelian genetics (see Sect. 15.2 for historical background), but in contemporary genetics we know that there are no such genes. The consequence of teachers using such convenient figures of speech might be to promote a

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[21] http://avida-ed.msu.edu/

[22] www.stauffercom.com/evolve4/

[23] www.*worldmaker.cite.hku.hk/worldmaker/pages/icce98-wrldmkr2.doc*

[24] http://intro.bio.umb.edu/VGL/

deterministic understanding of genetics among students. This should be an interesting area for future research. In what ways are teachers using language in their communication of genetics in the classroom?

Anthropomorphic metaphors of DNA have also been identified as frequent descriptions of DNA in popular sciences magazines in Sweden, where genes and DNA are referred to as intentional agents that "decide," "choose," and "remember" (Pramling and Säljö 2007). This seems to be universal phenomena as shown by the many studies that have identified media as depicting genes as deterministic causes of human behavior or disease (e.g., Condit et al. 1998, 2001; Carver et al. 2008; Nelkin and Lindee 1995). A question that would be interesting to pursue is if and in what ways students' understanding is influenced by the media and textbook (Castéra et al. 2008b; Gericke et al. 2012) discourse of genetic determinism. The impact of media on students' understanding has been investigated in Taiwan. Genetic concepts (gene, DNA, protein, chromosome, cell, biotechnology, and genetic engineering) were found to be among the most frequently mentioned science concepts in the media, but students had lower levels of knowledge of these biological concepts than of physics and earth science concepts, which were less frequently mentioned in the media (Rundgren et al. 2012; Tseng et al. 2010). In contrast, Donovan and Venville (2012) reported from a study of 62 children that "mass media [sic] is a persuasive teacher of children, and that fundamental concepts could be introduced earlier in schools to establish scientific concepts before misconceptions arise" (Donovan and Venville 2012, p. 1).

Argumentation skills, an instructional aim (also addressed above within Sect. 15.3.3 regarding SSI), have also been shown to be useful in enhancing reasoning and thinking, as well as conceptual understanding, in genetics. Zohar and Nemet (2002) found that integrating explicit teaching of argumentation into the teaching of dilemmas in human genetics enhanced the students' performance in both conceptual knowledge and argumentation. Similarly, facilitation of 10th-grade student use of argumentation about SSI while learning about genetics resulted in significant gains not only in complexity and quality of arguments used by students but also better genetics understanding compared to students in a comparison class (Dawson and Venville 2010; Venville and Dawson 2010) (see also Sect. 15.3.3 on SSI). This work looks at the effects of explicit instruction in argumentation skills as well as genetics on argumentation skills themselves. Sadler and Zeidler (2005) have revealed that student reasoning patterns about genetic engineering issues are influenced by their knowledge of genetics. Several studies have shown many other factors influence students' way of arguing in decision-making, including moral considerations, personal experiences, and popular culture (Dawson and Venville 2009; Sadler and Zeidler 2004). These research programs have been fruitful to date, achieving goals both of conceptual understanding and of reasoning and thinking skills.

Other innovative instructional approaches that are not explicitly informed by HPS but are worthy of mention for completeness include the use of so-called clicker questions within lectures (Knight and Smith 2010), use of the learning cycle (Dogru-Atay and Tekkaya 2008), and problem-based learning (Araz and Sungur 2007).

Using genetics as a vehicle for advancing cognitive skills, thinking, and reasoning is a promising research approach. The research reviewed above suggests a number of unanswered questions: What generalized cognitive skills gains are achievable through genetics instruction? What skills are appropriate and at what age levels given the limits of cognitive development? To what extent are the cognitive skill aims and the conceptual understanding aims mutually supportive? To what extent are these skill gains transferrable to other domains in biology (e.g., evolution) and beyond—especially outside the classroom? Are there thinking and reasoning skills that could be effectively targeted during genetics instruction (e.g., other than modeling and argumentation)? What instructional techniques are most effective at achieving each?

15.4 Closing Remarks

In this chapter we first gave a short overview of the history of genetics and its philosophical implications, emphasizing the development of the concept of the gene. The purpose of this overview is to provide a framework from which the reader can interpret the educational research reviewed in this chapter. For the interested reader there is a vast amount of scholarship about the history and philosophy of genetics available[25]. At the center of this literature is the idea of the gene and how it should be understood. The historical overview identified several important philosophical issues within genetics: (I) The gene concept has undergone a historical development in which the meaning of the concept changed. Today several different models or concepts are used to define the gene (more even than we could address in this paper). (II) The gene is a polysemous concept and it is not possible to reduce one of the multiple concepts (or models) into another. The descriptions of the gene are sometimes incoherent and context dependent. (III) One of the major reasons for incoherence is that different concepts or models are valid at different biological organizational levels. (IV) Another of the main reasons for the incoherence is that the different concepts (or models) define biological function and structure differently. (V) The simple concepts or explanatory models derived from classical genetics and early molecular genetics can promote a deterministic notion of the gene and genetics not in line to contemporary genomics.

It is important for an educator to know about the history of genetics and its philosophical implications because of the pervasiveness of historical ideas in school curricula (Gilbert et al. 2000) (see, e.g., the textbook studies in this and the following chapter). In school we seldom teach about the frontier of research. Interestingly though, in opposition to the typical historical focus of school genetics, we do most often teach about the new technological applications of biotechnology and genetic engineering. Here is an interesting dichotomy that needs further investigation. Very

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[25] See, for example, Carlson (1966, 2004), Davis (2003), Keller (2005), Moss (2003), Portin (1993), Sapp (2003), and Schwartz (2008).

few educational studies relate to more modern concepts such as genomics and proteomics. How is the modern radical shift toward genomics in research reflected in school science?

In Sect. 15.3 of this chapter, we identify scholarship that implicitly or explicitly uses the HPS as a point of reference in designing genetics instruction. The primary focus of the section is on the contributions of HPS scholarship on the following: (I) teaching and learning genetics, (II) enhancing the teaching and learning of NOS, (III) humanizing science, and (IV) enhancing reasoning, argumentation, and thinking skills. We identified the following main HPS themes: (I) Students tend to appropriate conceptions from classical genetics and simple molecular models that often lead to deterministic understandings of genetics. Moreover students have difficulties in relating concepts and in moving between different biological organizational levels. These overall conclusions from science education research could be explained by the philosophical issues of reduction and the polysemous gene concept. Including main philosophical issues in education could help students tackling these learning problems. (II) Many studies reported positive effects of a HPS perspective in genetics teaching on learning NOS. This trend was anticipated, given that the NOS, i.e., how we build scientific knowledge, is essentially a question of epistemology. When focusing genetics instruction on NOS, there are many interesting narratives to use: competing theories and models to contrast, different theoretical approaches to elucidate, a technical development in scientific applications to compare, etc. (III) Researchers have also used historical narratives in genetics to humanize genetics instruction in a variety of fruitful ways, including social aspects such as gender, ethics, and language as well as darker topics such as eugenics. (IV) Finally some of the better studied areas within genetics education include the use of argumentation, problem-solving, and narratives. However these areas have to a lesser degree, than the previous, been illuminated by HPS. Therefore, there is a need for further studies of genetics teaching and learning that are informed by a HPS perspective.

Although the research reviewed in this chapter is a good start, it seems to us that many of the teaching and learning issues addressed in these recommendations have been widely recognized at least for decades and that much more explicit guidance is needed. In recent years two workshops have taken place that addressed the questions of how to redesign science curricula for the genomics era (Boerwinkel and Waarlo 2009; Boerwinkel and Waarlo 2011), and much of the discussions in these workshops are relected in Sect. 15.3.1 above. The efforts of these workshop organizers are praiseworthy and a new workshop is planned for 2013. The issue of HPS, however, has not been a dominant part of the agenda of those workshops, and we encourage the genetic education research community to reconsider the value of the HPS lens. Questions that should be asked include: How might careful attention to HPS issues help to expand this list? What, for example, are the most effective ways to use the history of genetics and/or genetic case studies to enhance genetics understanding? More specifically, how should the history of our understanding (and definition) of the gene be presented to students? What does philosophy (especially epistemology) have to say that informs decisions about what working definitions to present to students? How can HPS inform curriculum design so as to best prepare students to be wise medical consumers in the twenty-first-century era of personalized genomics and pharmacogenetics?

In conclusion, HPS has been applied to genetics education in a variety of ways, but in most areas there is a need for more educational research in which HPS is used as a guiding framework. Much of the relevant scholarship relates to HPS only in a largely implicit way. HPS-informed approaches appear to be fruitful avenues for improving and understanding genetics teaching and learning. We hope that researchers will continue to use these approaches and that the questions we have raised throughout this chapter will both guide further research and stimulate the generation of even more fruitful research questions.

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Chapter 16
The Contribution of History and Philosophy to the Problem of Hybrid Views About Genes in Genetics Teaching

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16.1 Introduction

The gene concept has been one of the landmarks in the history of science in the twentieth century, which has been even characterized as "the century of the gene" (Gelbart 1998; Keller 2000). However, there are nowadays persistent doubts about the meaning and contributions of this concept, not only among philosophers of biology[1] but also among empirical scientists.[2] Moreover, by the mid-2000s concerns about the gene extended to the editorials of high-impact scientific journals (e.g., Pearson 2006).

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[1] See, for example, Burian (1985), Falk (1986), Fogle (1990), Hull (1974), and Kitcher (1982).

[2] See, for example, Gerstein et al. (2007), Kampa et al. (2004), Venter et al. (2001), and Wang et al. (2000).

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There are negative and positive reactions to the problem of the gene or, as El-Hani (2007) describes, attempts to eliminate this concept from biology or to keep it although radically reconceptualized. Keller (2000), for instance, suggested that maybe the time was ripe to forge new words and leave the gene concept aside (see also Portin 1993; Gelbart 1998). More optimistic views are found, for example, in Hall (2001), who argued that, despite published obituaries, the gene was not dead, but alive and well, and seeking a haven from which to steer a course to its "natural" home, the cell as a fundamental morphogenetic unit, or in Knight (2007), for whom "reports of the death of the gene are greatly exaggerated."

The crisis of the gene concept is mostly related to its interpretation as *a stretch of DNA that encodes a functional product, a single polypeptide chain or RNA molecule*, that is, the so-called classical molecular gene concept (Neumann-Held 1999; see also Griffiths and Neumann-Held 1999; Stotz et al. 2004). Under the influence of this concept, simple and straightforward one-to-one relationships (function = gene = polypeptide = continuous piece of DNA = cistron) were regarded as acceptable in understanding the functioning of the genetic system from the 1940s to the 1970s (Scherrer and Jost 2007a, b). These relationships were captured in a manner that was heuristically powerful in genetics and molecular biology, which benefited from treating the gene as an uninterrupted unit in the genome, with a clear beginning and a clear ending and with a single function ascribed to its product (and, thus, indirectly to the gene). The explanatory and heuristic power of this concept follows from how it brought together structural and functional definitions of the gene, alongside with an easily understandable mechanics. With the introduction of an informational vocabulary in molecular biology and genetics (Kay 2000), genes were also regarded as informational units, leading to what has been called the informational conception of the gene (Stotz et al. 2004), a popular notion in textbooks, the media, and public opinion.

This picture changed since the 1970s, as the view of the gene as a structural and functional unit was increasingly challenged by anomalies resulting from research mostly conducted in eukaryotes, in which we find nothing like the tight physical complex linking transcription and translation observed in bacteria. We can classify these anomalies in three kinds, all related to counterevidence for a unitary relationship between genes, gene products, and gene function: (i) *one-to-many* correspondences between DNA segments and RNAs/polypeptides (as, for instance,

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in alternative splicing,[3] Black 2003; Graveley 2001), (ii) *many-to-one* correspondences between DNA segments and RNAs/polypeptides (as in genomic rearrangements, such as those involved in the generation of diversity in lymphocyte antigen receptors in the immune system[4]; see Cooper and Alder 2006; Murre 2007), and (iii) *lack of correspondence* between DNA segments and RNAs/polypeptides (as we see, e.g., in mRNA editing[5]; see Hanson 1996; Lev-Maor et al. 2007).

Another key issue related to the gene concerns conceptual variation and ambiguities throughout its history (e.g., Carlson 1966). As Rheinberger (2000) argues, genes can be regarded as "epistemic objects" in genetics and molecular biology, entities introduced and conceived as targets of research, whose understanding is framed by the set of experimental practices used by particular scientific communities. Thus, conceptual variation can be explained as a consequence of different experimental practices used by diverse communities of scientists who deal with genes as epistemic objects (Stotz et al. 2004). For instance, population geneticists often work with an instrumental view of genes as determinants of phenotypic differences, since this is often enough to deal with the relationship between changing gene frequencies in populations over time and changes in the phenotypes of the individuals making up those populations. They tend to emphasize, thus, genes as markers of phenotypic effects, taking a more distal view on gene function. Molecular biologists, in turn, focus their attention on genes in DNA and their molecular products and interactions, emphasizing the structural nature of genes and their role in the cellular system they are part of. They take a more proximal view of genes and tend to be reluctant to identify a gene by only considering its contributions to relatively distant levels of gene expression (Stotz et al. 2004).

The phenomenon at stake here is gene function, and consequently, we will refer to multiple models of gene function, in the structure of which a central element is the gene concept.[6] The experimental practices used by diverse scientific communities

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[3] In alternative splicing, a pre-mRNA molecule is processed – in particular, spliced – in a diversity of manners, so that different combinations of exons emerge in the mature mRNA. In this manner, several distinct mRNAs and, thus, polypeptides can be obtained from the same DNA sequence. In *Drosophila melanogaster*, for instance, DSCAM alternative splicing can lead to ca. 38,016 protein products (Celotto and Graveley 2001).

[4] The generation of the diverse antigen receptors found in lymphocytes and, consequently, of antibody specificity depends on a combinatorial set of genomic rearrangements between different DNA segments called variable segments, constant segments, and diversity and joining segments.

[5] mRNA editing is an alteration of mRNA nucleotides during processing, resulting in lack of correspondence between nucleotide sequences in mature mRNA and nucleotide sequences in DNA.

[6] "Model" is a polysemous term, with diverse meanings that capture distinct relationships between elements of knowledge (e.g., Black 1962; Grandy 2003; Halloun 2004, 2007; Hesse 1963). We treat models here as constructs created by the scientific community in order to represent relevant aspects of experience, i.e., phenomena and processes/mechanisms that can explain and/or predict them. In these terms, models capture the relationship between a symbolic system (a representation) and phenomena, processes, and mechanisms ontologically treated as being part of the world or nature. Models are built through processes of generalization, abstraction, and idealization that crucially involves selecting a number of entities, variables, relationships associated with a specific class of phenomena and processes/mechanisms to be included in the model, while others are

lead to variation in models of gene function and gene concepts. The expression "conceptual variation" describes, then, the range of different meanings ascribed to a concept, not necessarily all of them outdated, since they may still be used in different contexts.

Conceptual variation has been heuristically useful in the history of genetics.[7] Different gene concepts and different gene function models have been and still are useful in different areas of biology, with different theoretical commitments and research practices. Nevertheless, while recognizing that conceptual variation is a desirable feature in our understanding of genes, several authors stress that we should clearly distinguish between different concepts and models, with diverse domains of application.[8] After all, conceptual variation may also lead to misconceptions and misunderstandings. Falk (1986, p. 173), for instance, considers that the pluralism found in the current picture about genes "… brought us […] dangerously near to misconceptions and misunderstandings." Fogle (1990, p. 350) argues that "despite proposed methodological advantages for the juxtaposition of 'gene' concepts it is also true […] that confusion and ontological consequences follow when the classical intention for 'gene' conjoins a molecular 'gene' with fluid meaning." Keller (2005) argues that many problems arise from ambiguities in the usage of the term "gene," calling attention to difficulties with gene counting, since the value obtained may vary by two, three, or more orders of magnitude depending on how genes are defined.

Diversity in meaning and heterogeneity in reference potential can lead to semantic incommensurability, although this is not necessarily so. In the history of genetics, ideas associated with different ways of understanding genes and their roles in living systems have been sometimes merged in the construction of new concepts and models. However, one needs to consider that conceptual change often leads to scientific concepts with heterogeneous reference potentials and, thus, to models with diverse meanings, and as a result, there can be semantic incommensurability between concepts and models. When semantically incommensurable models and concepts, or even some of their features, are mixed up, logical inconsistencies and conceptual incoherence can appear.

In science, conceptual variation and the combination of ideas related to different models are usually (but not always) less problematic, since researchers usually develop a sophisticated understanding of the knowledge base of their research field (even though much can remain tacit) and also learn epistemic practices that stabilize

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selected out. These entities, variables, and relationships are captured by scientific concepts, and thus, a model can be seen as a system of related concepts. Concepts gain meaning by being used in model construction, as contributors to model structure (Halloun 2004). If we understand scientific theories as families of models – according to a semantic approach (e.g., Develaki 2007; Suppe 1977; van Fraassen 1980) – concepts will form a network of relationships as a consequence of their participation in a series of models, and ultimately, the meaning of a concept will be constructed out of its relationship with other concepts in a network of models.

[7] See, for example, Burian (1985), Falk (1986), Griffiths and Neumann-Held (1999), Kitcher (1982), and Stotz et al. (2004).

[8] For instance, El-Hani (2007), Falk (1986), and Griffiths and Neumann-Held (1999).

to a significant extent the use of concepts and models. They are embedded in a community committed to a specific set of epistemic practices that make it more likely that they employ particular meanings ascribed to gene concepts and gene function models, which properly operates in a given domain of investigation. They also tend to recognize the prospects and limits of different concepts and models. This does not mean that concepts and models are per se stabilized when they emerge in the scientific community. On the contrary, they usually appear in a more rudimentary way, and if they are adopted by the scientific community, they can be elaborated and eventually stabilized by the practice of using them to guide research. When concepts and models are fused, the scientific community may be able to work out possible incoherence. However, as the diversity of concepts and models expands – as we see in the case of genes in the post-genomic era – difficulties are more likely to arise, particularly in the absence of a clear and explicit demarcation between those diverse meanings. This means that we should not remain content with the tacit usage of distinct meanings in different research settings, but rather worry about the clear demarcation of their domains of application (El-Hani 2007).

Certainly, teachers and students are embedded in a number of communities just as scientists are part of the scientific community. Every human being participates in a number of communities, which shape their understanding of the world. They can be described, if we follow Wenger (1998), as "communities of practice" (CoPs), cohesive groups of individuals mutually engaged in a joint enterprise, who exhibit distinct sets of knowledge, abilities, and experiences, and are actively involved in collaborative processes, sharing information, ideas, interests, resources, perspectives, activities, and, above all, practices, such that they build a shared repertoire of knowledge, attitudes, values, etc. (see also Lave and Wenger 1991). In the scientific community, we can find CoPs which generate a shared repertoire of knowledge, epistemic practices, and values that can stabilize the understanding of theories, models, and concepts to varying degrees. This means that scientists build a collective empiricism (Daston and Galison 2010) that often allows them to deal with a variety of models and concepts in a more consistent way. Or, to put it differently, persons tend to form "thought collectives," communities that mutually exchange ideas and develop a given "thought style" (Fleck 1979/1935). What is at stake here, then, is that scientists, teachers, and students pertain to different communities of practice, if we follow Wenger's formulation or, thought collectives, if we follow Fleck's and, thus, will tend to assume different perspectives on the diversity of scientific models and concepts. And the fact that scientists can be embedded in communities that generate that very diversity is of the utmost importance here.

When we turn to science education, we have additional reasons to worry about conceptual variation about genes and their function and the hybridization of different gene concepts and gene function models, as argued by Gericke and Hagberg (2007, 2010a, b), Gericke et al. (in press), and Santos et al. (2012). After all, even though teachers and students are themselves embedded in CoPs or thought collectives, they are not embedded in those scientific communities that generate knowledge about genes and their function. Moreover, in educational settings conceptual variation tends to be greater than in the scientific community, since both scientific and everyday meanings are represented and interact with each other within classrooms (Mortimer and Scott 2003), and disciplinary boundaries which may stabilize meaning making are not always present. In sum, when compared to the scientific community, there is much more potential to indiscriminate mixture of semantically incommensurable scientific concepts and models in the science classroom and, thus, a much bigger potential that logical inconsistencies and conceptual incoherence emerge. This is particularly true when science is taught without due attention to its history and philosophy.

It is important, therefore, to investigate whether and how conceptual variation related to the gene concept and gene function models is present in school science and also what potential problems it may bring to genetics teaching and learning. In this chapter, we will survey the results of a research program conducted in our lab in the last 7 years, focusing on how ideas about genes and gene function are treated in school knowledge, as represented in textbooks and students' views. Moreover, following our usual approach to research on science education, we move from descriptive to intervention studies, i.e., from diagnosing views on genes to investigating a teaching strategy implemented in a classroom setting with the goal of changing higher education students' views and, in particular, improving their understanding of scientific models and conceptual variation around genes and their function. Here, we will first consider results from investigations on how higher education and high school textbooks deal with genes, gene function, and their conceptual variation. Second, we will report unpublished results concerning how higher education biology students deal with genes and gene function. Third, we will present findings of an unpublished intervention study in which we investigate design principles for teaching sequences about genes and their function, considering conceptual variation in genetics and molecular biology, the crisis of the gene concept, and current proposals for revising its meaning. As a background for these empirical researches, we will turn to their theoretical underpinnings, resulting from both the literature on philosophy of biology/theoretical biology and the educational literature.

16.2 Genes and Gene Function Through the History of Genetics

The term "gene" was created in 1909, by Johannsen, following his distinction between genotype and phenotype, which told apart two ideas embedded in the term "unit character," then largely used, (1) a visible character of an organism which behaves as an indivisible unit of Mendelian inheritance and, by implication, (2) the idea of that entity in the germ cell that produces the visible character (Falk 1986). Johannsen proposed, then, the existence of basic units composing the genotype and phenotype, respectively, "genes" and "phenes." While the latter term never gained currency in biology, the former became central in newborn genetics and marked its development throughout the twentieth century.

Genes were seen instrumentally in the beginnings of genetics. Johannsen conceived "gene" as a very handy term with no clearly established material counterpart (Johannsen 1909). Although accepting that heredity was based on physicochemical processes, he warned against the conception of the gene as a material, morphologically characterized structure. For Johannsen, "the gene is [...] to be used as a kind of accounting or calculating unit" (Johannsen 1909; See Falk 1986; Wanscher 1975). At that period, the gene (that "something" which was the potential for a trait) could only be inferred from its "representative," the trait. That is, the gene was defined top-down, based on the phenotype.

This way of understanding genes is part of the Mendelian model of gene function, as reconstructed by Gericke and Hagberg (2007). According to this model, the gene is the unit of transmission (or inheritance) and function, treated as an abstract entity interpreted instrumentally as a phenotype in miniature. The function of the gene is of minor importance in the Mendelian model, focused on explaining genetic transmission. Moreover, due to the instrumental nature of the gene and its definition from the phenotype, this model conceives the gene as a necessary and sufficient condition for the manifestation of a trait, with no consideration of environmental or any other factor besides those instrumental entities. Thus, it assumed a unitary relationship between genes and traits, and the idea of genes as units became central in Mendelian genetics, thereafter substantially influencing twentieth century biology.

With the establishment of the chromosome theory of heredity by T. H. Morgan and his group, a new understanding of genes emerged (Carlson 1966). This understanding amounts to Gericke and Hagberg's (2007) classical model of gene function. The gene acts, in this model, as the unit of genetic transmission, inheritance, function, mutation, and recombination (Mayr 1982). Two additional important ideas are that genes exist in different variants (alleles) and consist or act as enzymes that produce traits. Since the molecular structure of genes was unknown, this latter idea was vague, and genes and their function were still inferred from traits. This model treated genes, however, as more active in the determination of traits than the Mendelian model did. Due to the development of linkage maps by Alfred Sturtevant, from Morgan's group, genes came to be interpreted in terms of the beads-on-a-string concept. Those quantified particles in the chromosomes were increasingly seen in realist rather than instrumentalist way, despite Morgan's hesitation (Falk 1986). Another notorious member of Morgan's group, Herman J. Muller, was one of the first supporters of the idea that genes were material units, "ultramicroscopic particles" in the chromosomes, arguing against the description of the gene as "a purely idealistic concept, divorced from real things" (quoted by Falk 1986). This view paved the way for subsequent steps in a research program aiming at elucidating the material bases of inheritance.

With a minor modification resulting from biochemical studies on the nature of genes, what Gericke and Hagberg (2007) call the biochemical-classical model of gene function emerged. The gene was treated, then, as being responsible for the production of a specific enzyme, which produced a trait. Also, as increased knowledge on biochemical reactions became available, the focus shifted from transmission to gene action and function. The biochemical-classical model explained gene function by reducing it to the relationship between a specific enzyme produced by the gene and the determination of a phenotypic trait. The model did not explain, however, the biochemical processes involved, and consequently, it still used the conceptual tools of classical genetics. The biochemical-classical gene was still an entity with unknown molecular structure.

The biochemical-classical model is the origin of the famous "one gene-one enzyme" hypothesis, which suffered several reformulations with increasing knowledge: when it was shown that the gene product was not always an enzyme, there was a shift to the "one gene-one protein" hypothesis, and when it was shown that proteins could be composed by several polypeptides, the "one gene-one polypeptide" hypothesis emerged. Finally, when it was established that RNAs could also be final gene products, the "one gene-one polypeptide or RNA" hypothesis prevailed. Notice, however, that an important shared content in all these hypotheses is that genes are treated as units.

At first, the gene was conceived as a unit of transmission, recombination, function, and mutation, but this did not hold. Benzer (1957) showed that units of function (his "cistrons") are typically much larger than units of recombination ("recons") and mutation ("mutons"). The terms "muton" and "recon" were deleted from the vocabulary of genetics, but "cistron" survived to these days and is often used in the place of "gene," indicating that the idea that prevailed was that of the gene as "unit of function."

The molecular-informational model (Santos et al. 2012)[9] was the culmination of a series of investigations about the material nature of the gene, which ultimately led to the proposal of the double helix model of DNA by Watson and Crick (1953). This model explained in one shot the nature of the linear sequence of genes, the mechanism of gene replication and RNA synthesis from DNA sequences, and the separation of mutation, recombination, and function at the molecular level. It was responsible for the wide acceptance of a realist view about genes, since there was now a clear material counterpart for the gene concept. The stage was set for a molecular definition of genes, in which genes were not defined anymore in a top-down manner, based on phenotypic traits, but in a bottom-up approach, focused on nucleotide sequences in DNA. This was accomplished through a concept named by Neumann-Held (1999) the classical molecular concept of the gene. According to it, a gene is a DNA segment encoding one functional product, which can be either a RNA molecule or a polypeptide. This concept superimposed a molecular understanding onto the idea of a hereditary unit supported by Mendelian genetics (Fogle 1990) and played an important role in the transition from classical genetics to a new era in which genetics and molecular biology became inseparable.

In the classical molecular concept, the gene is a continuous and discrete DNA segment, with no interruption or overlap with other units, showing a clear-cut beginning and end, and a constant location. Genes can be treated, then, as units of structure and, provided that they codify a single RNA molecule or polypeptide with a single function, also as units of function. And, with the introduction of information talk in

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[9] This corresponds to Gericke and Hagberg's (2007) neoclassical model of gene function.

biology (Kay 2000) and in connection with the so-called central dogma of molecular biology, the gene became also a unit of information, simultaneously a chemical and a program for running life.[10] However, this idea is hardly trivial: despite the widespread usage of informational terms in molecular biology and genetics (say, "genetic information," "genetic code," "genetic message," "signaling,"), they can be still regarded as metaphors in search of a theory (El-Hani et al. 2006, 2009; Griffiths 2001). We do not have yet a sufficient and consistent theory of biological information, despite the utility of Shannon and Weaver's (1949) mathematical theory of communication for several purposes in biological research (Adami 2004). The non-semantic understanding of information in this theory seems insufficient for a theory of biological information. Many authors argue that biology needs a theory of information including syntactic, semantic, and pragmatic dimensions (e.g., El-Hani et al. 2006, 2009; Hoffmeyer and Emmeche 1991; Jablonka 2002). Notwithstanding, genes are frequently treated as informational units, leading to the informational conception of the gene (Stotz et al. 2004), which is often superimposed onto the classical molecular concept even though it does not have a clear meaning.

As discussed in the introduction, several findings of genetic, molecular, and genomic research challenged in the last three decades the molecular-informational model, posing problems for the understanding of a gene as a unit of structure, function, and/or information. Even though the crisis of this model was more widely recognized in the last two decades of the twentieth century, many-to-many relationships were known to classical genetics already. Benzer, for instance, regarded the gene as a "dirty word" (Holmes 2006).

Gericke and Hagberg (2007) introduce a "modern model" to encompass these challenges, in which the gene is treated as a combination of DNA segments that acts in a process that defines the function. This stretch of DNA contains regulating sequences and a transcription unit, made of coding sequences, but also introns and flanking sequences. It is expressed to produce one or several functional products, either RNAs or polypeptides. Smith and Adkison (2010) complemented this account by considering two further elements: (1) the findings of the Human Genome Project, such as the relatively limited number of genes in human and other genomes, when compared to previous estimates, and the similarity in gene numbers between humans and other animals, and (2) the definition of gene proposed by the ENCyclopedia Of DNA Elements (ENCODE) project.[11] We need to be careful,

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[10] This shows the connection between the informational conception of the gene and genetic determinism (Oyama 2000/1985), a common element of the "gene talk" (Keller 2000) that pervades the media and the public opinion. With the central dogma, DNA became a sort of reservoir from where all "information" in a cell flows and to which it must be ultimately reduced. Through their connection with the doctrine of genetic determinism, the conceptual problems related to genes and genetic information have important consequences for public understanding of science and several socioscientific issues related to genetics and molecular biology (say, genetic testing, cloning, genetically modified organisms).

[11] The ENCODE project is an international consortium of scientists trying to identify the functional elements in the human genome sequence, with significant impact on our understanding about genes and genomes. The ENCODE database can be reached at http://www.genome.gov/10005107#4.

however, in referring to a "modern model," since this may mask the fact that there is no prevailing model nowadays. The gene concept is now in flux, changing meanings as researchers produce novel interpretations of the structure and dynamics of the genomic system.

Several proposals for reformulating the gene concept appeared in the last 20 years. We will just mention some of them here, with no intention of being exhaustive or providing any detailed discussion.[12] Some authors argued against the idea of genes as units and proposed, instead, views about genes as combinations of nucleic acid sequences that correspond to a given product (Fogle 1990, 2000; Pardini and Guimarães 1992) and might be located in processed RNA molecules (Scherrer and Jost 2007a, b). These proposals accommodate anomalies such as overlapping and nested genes by denying the idea of genes as units in DNA.

Other authors put forward a process-oriented view of genes.[13] In Neumann-Held's "process molecular gene concept," for instance, genes are not treated as "bare DNA" but as the whole molecular process "… that leads to the temporally and spatially regulated expression of a particular polypeptide product" (Griffiths and Neumann-Held 1999, p. 659). Since different epigenetic conditions that affect gene expression are in this way built into the gene, this proposal can accommodate anomalies such as alternative splicing or mRNA editing.

Moss (2001, 2003) distinguished between two meanings ascribed to genes and, consequently, demarcated two concepts, gene-P and gene-D, which have been usually conflated throughout the twentieth century. Gene-P amounts to the gene as determinant of phenotypes or phenotypic differences. It is an instrumental concept, not accompanied by any hypothesis of correspondence to reality, and this is what allows one to accept the simplifying assumption of a preformationist determinism (as if the trait was already contained in the gene, albeit in potency). Gene-P is useful to perform a number of relevant tasks in genetics, such as pedigree analysis or genetic improvement by controlled crossing methods. Gene-D amounts to the gene as a developmental resource in causal parity (Griffiths and Knight 1998) with other such resources (say, epigenetic ones). It is conceived as a real entity defined by some molecular sequence in DNA which acts as a transcription unit and provides molecular templates for the synthesis of gene products, being in itself indeterminate with respect to the phenotype (Moss 2003, p. 46). Gene-D is in accordance, thus, with the classical molecular concept. Moss argues that genes can be productively conceived in these two different ways, *but nothing good results from their conflation* (Moss 2001, p. 85). This conflation is one of the main sources of genetic determinism, with important consequences to socioscientific issues, since it leads to the idea of

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The participants of the ENCODE can be found at http://www.genome.gov/26525220. See also The ENCODE Project Consortium (2004).

[12] For detailed discussion, see Meyer et al. (2013). When we consider these views about genes and their function, it is worth pondering about the school level to which they can be adequately transposed. This issue is also discussed by Meyer et al. (2013).

[13] See, for example, El-Hani et al. (2006, 2009), Griffiths and Neumann-Held (1999), Keller (2005), and Neumann-Held (1999, 2001).

genes as major or even single causal determinants of phenotypic traits, even highly complex traits, such as sexual orientation, intelligence, or aggression.

Among the contributions of the ENCODE project, we find a new definition of gene: "*… a union of genomic sequences encoding a coherent set of potentially overlapping functional products*" (Gerstein et al. 2007, p. 677, emphasis in the original). In this definition, different functional products of the same class (proteins or RNAs) that overlap in their usage of the same primary DNA sequences are combined in the same gene, and thus, several anomalies are accommodated by challenging the unitary relationship between genes, gene products, and gene function embedded in the classical molecular concept.

Some works strive for solving the gene problem by building new languages that cut up the genetic system into novel categories, organizing our understanding into different sets of concepts (Keller and Harel 2007; Scherrer and Jost 2007a, b). On the one hand, this may solve, or dissolve, problems and limits posed by our current language about genes. On the other, there is an expected difficulty of translation between the new languages and the one already established in the fields of genetics and molecular biology, which may hamper researchers' understanding of those new ways of speaking and, thus, their acceptance. To maintain sufficient bridges between new and older ways of speaking seems crucial, then, for the success of these proposals.

When we consider these new views about genes and their function, it is worth pondering about the school level to which they can be adequately transposed. This is not the space, however, to enter this discussion (see Meyer et al. 2013).

16.3 Methods

16.3.1 Textbook Studies[14]

16.3.1.1 Sample

We analyzed higher education and high school textbooks. A sample of higher education Cell and Molecular biology textbooks was selected through a survey of 80 course syllabi of 67 universities located in the 5 continents, randomly chosen in Google® searches performed in 2004. We analyzed three of the most used textbooks, respectively, Lodish et al. (2003, n = 33 syllabi, the most used), Alberts et al. (2002, n = 28, the second most used), and Karp (2004, n = 5, the fifth most used). In many countries these textbooks are used in their original language, although it is possible to find translations. Thus, we analyzed them in the original language.

Eighteen biology textbooks (see Appendix 1) submitted by publishing companies to the Brazilian National Program for High School Textbooks (PNLEM) (El-Hani et al. 2007, 2011) were analyzed. This sample shows external validity regarding

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[14] For more details, see Santos et al. (2012) and Pitombo et al. (2008).

Brazilian textbooks. PNLEM is a huge governmental initiative, providing textbooks to students enrolled in public high schools throughout the country. These textbooks are aimed at general high school biology courses attended by all students, covering all areas of biology. Besides being distributed to public schools by PNLEM, most of these textbooks are also used by private schools.

16.3.1.2 Textbook Content Analysis

Each textbook was analyzed as a whole using categorical content analysis (Bardin 2000). The procedure involved, first, the decomposition of the texts into units of analysis (recording units), from which categories were built through regroupings of text elements sharing characteristics identified by semantic criteria, i.e., by the presence of the same meaning in different text elements, not by the occurrence of specific keywords or sentences. First, an exploratory reading was performed to plan the decomposition of the texts, data treatment, and categorization. Besides the units of recording, we also considered units of context, larger segments of text embedding the units of recording, which provided a background for interpreting them. Recording units were the basic units for categorization and frequency calculation, varying in size from a single statement to a whole paragraph.

Since different areas of biology use particular epistemic practices, which lead to the creation of distinct ways of thinking and speaking about genes, most units of context were related to biological subdisciplines. In high school textbooks, they were characterization of life and/or living beings (i.e., the introductory chapters in the textbooks), cell and molecular biology, genetics, evolution, and glossary.[15] In higher education textbooks, the following units of context were employed: classical genetics, developmental genetics, evolutionary/population genetics, genetics of microorganisms, genetics of eukaryotes, medical genetics, molecular biology/molecular genetics, cell biology, biochemistry, cell signaling, genetic engineering, genomics, introduction, history of science, and glossary.[16]

Higher education textbooks were analyzed by using categories informed by the historical, philosophical, and scientific literature about genes. In high school textbooks, we employed three analyzing procedures: (1) analysis of gene concepts and (2) analysis of function ascription to genes, both based on the abovementioned literature, and (3) analysis of historical models of gene function, as described by Gericke and Hagberg (2007). In the latter analysis, we used the research instrument built by these authors, with some changes, to investigate how the variants associated with each of the seven epistemological features of the historical models were found in the recording units (Table 16.1).

Depending on the combination of epistemological feature variants used in an explanation of gene function, the explanation present in the recording unit can be classified into the historical models (Table 16.2). However, in school science, models are often reconstructed in a nonhistorical way, due to neglect of their historical

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[15] Only 4 textbooks had a glossary. All other units of contexts were present in all textbooks.

[16] A glossary was present in all the textbooks.

Table 16.1 Description of the epistemological feature variants used in the high school textbooks analyses

Epistemological features		Epistemological feature variant	
1	The structural and functional relation to the gene	**1a**	The gene is an abstract entity and, thus, has no structure
		1b	The gene is a particle on the chromosome
		1c	The gene is a DNA segment
		1d	The gene consists of one or several DNA segments with various purposes
		1e	**The gene is a carrier, bearer, and/or unit of information**
2	The relationship between organization level and definition of gene function	**2Ia**	The model has entities at the phenotypic level and abstract concepts[a]
		2Ib	The model has entities at the phenotypic and cell levels[a]
		2Ibx	The model has entities at the phenotypic, cell, and molecular levels[a]
		2Ic	The model has entities at the molecular level
		2Icx	The model has entities at the cell and molecular levels
		2Icy	**The model has entities at the phenotypic and molecular levels**[a]
		2IIa	The correspondence between gene and its function is one-to-one
		2IIb	The correspondence between gene and its function is many-to-many
3	The 'real' approach to define the function of the gene	**3a**	The function of the gene is defined "top-down"
		3b	The function of the gene is defined "bottom-up"
		3c	The function of the gene is defined by an underlying process related to the capacity of expressing a particular gene product[b]
4	The relationship between genotype and phenotype	**4a**	There is no separation between genotype and phenotype
		4b	There is a separation, without explanation, between genotype and phenotype
		4c	There is a separation between genotype and phenotype with enzyme as intermediate causal explanation[b]
		4d	There is a separation between genotype and phenotype, explained by biochemical processes
5	The idealistic *versus* naturalistic relationships in the models	**5Ia**	There are idealistic relations in the model, with no reference to natural processes[b]
		5Ib	There are naturalistic relations in the model, with a detailed description of the biochemical process of gene expression[b]
		5IIa	The relations in the model are causal and mechanistic (chemical interactions of genes determine traits independently of context)[b]
		5IIb	The relations in the model are process oriented and holistic (the function of the gene depends on the context in which it is embedded)[b]
6	The reduction explanatory problem	**6a**	There is explanatory reduction from the phenotypic level to abstract concepts[a]
		6b	There is explanatory reduction from the phenotypic to the cell level[a]
		6bx	There is explanatory reduction from the phenotypic level to the molecular level[a]
		6c	There is no explanatory reduction
7	The relationship between genetic and environmental factors [in development and the construction of the phenotype]	**7a**	Environmental entities are not considered
		7ax	Environmental entities + genetic entities result in a trait/product/function[a]
		7b	Environmental entities are implied by the developmental system
		7c	Environmental entities are shown as part of a process

Variants in gray were introduced by Santos et al. (2012) in the original research instrument constructed by Gericke and Hagberg (2007)

[a] Changes in terminology introduced by Santos et al. (2012) in the epistemological feature variants

[b] Variants modified by Santos et al. (2012) in order to make some aspects more explicit

[c] The relationship is understood in additive terms, each factor being related to the product, but with no significant mutual influence between them

and epistemological backgrounds during didactic transposition (Justi and Gilbert 1999). Thus, hybrid models are often found, i.e., explanatory models consisting of aspects belonging to different historical models, which may be incoherent if incommensurable aspects are mixed up. We calculated the degree of model hybridization in textbook explanations of gene function, by ascertaining the frequency of

Table 16.2 Models of gene function and their epistemological feature variants (Gericke and Hagberg 2007, modified by Santos et al. 2012)

	Epistemological feature variants								
Models of gene function	**1**	**2I**	**2II**	**3**	**4**	**5I**	**5II**	**6**	**7**
Mendelian model	1a	2Ia	2IIa	3a	4a	5Ia	5IIa	6a	7a
Classical model	1b	2Ib	2IIb	3a	4b	5Ia	5IIa	6b	7a
Biochemical-classical model	1b	2Ib	2IIa and 2IIb	3a and 3b	4c	5Ia	5IIa	6b	7a
Neoclassical (or molecular-informational) model	1c and 1e	2Ic	2IIa	3b	4d	5Ib	5IIa	6c	7b
Modern model	1d	2Ic	2IIa	3c	4d	5Ib	5IIb	6c	7c

false-historical (i.e., belonging to the wrong historical model) and nonhistorical (i.e., not present in any of the historical models) feature variants.

We analyzed the presence of historical models of gene function in the textbooks in two different ways. In a previous study (Santos et al. 2012), we identified feature variants related to these models in each set of chapters related to the domain of a biological subdiscipline and, then, checked the model to which most of the epistemological feature variants were linked. We identified, thus, the prevailing model at that set of chapters, while the other feature variants, either false historical or nonhistorical, allowed us to calculate the degree of model hybridization at that same portion of the textbook. In a subsequent work (Gericke et al. in press), we described which models of gene function prevailed in each chapter and, then, calculated the degree of hybridization based on false-historical and nonhistorical feature variants. In this work, we will consider only the latter analysis.

The analyses of higher education textbooks were performed by the same researcher in order to increase their reliability, while two other researchers examined all the analyses, comparing part of the results with the original textbooks. In the study about high school textbooks, internal reliability was increased by carrying out independent analyses of the recording units by two researchers (cf. LeCompte and Goetz 1982). Inter-rater agreement between these analyses was high, reaching 89.9 %. The two raters and a senior researcher discussed the diverging categorizations, looking for shared agreement, such that the findings amount to consensus reached by those three researchers. In four instances where no consensus was reached, the recording units were excluded from the analysis.

16.3.2 Study on Higher Education Students' Views About Genes and Their Functions

16.3.2.1 Sample

We investigated the views of 112 biology undergraduate students of two Brazilian universities (Federal University of Paraná, UFPR, hereafter U1 – 60, Federal University of Bahia, UFBA, hereafter U2 – 52 students) on genes and their functions. The sample from each university was subdivided according to whether or not they had already attended Genetics courses. All students that had already attended Genetics courses had also previously attended Cell and Molecular biology courses.[17]

16.3.2.2 Data Gathering Tool

We employed a questionnaire constructed and validated by ourselves, comprising three sections: (A) students' personal data, including information on his/her experiences on teaching and research training; (B) open and closed questions on genes, challenges to the classical molecular gene concept, and biological information; and (C) closed questions on the gene concept. Sections (B) and (C) contained 11 questions. Due to space constraints, we will consider only the results for three of them. The first is deliberately open ended and divergent, aiming at eliciting a diversity of answers: "In your view, what is a gene?" The other two are closed-ended questions, which were partly derived from Stotz et al. (2004). Both presented the same options for the students to mark, but one was a forced choice, while the other was a free-choice question. Here are the statements that the students could choose with the understanding of genes closer to each shown within brackets (information not available for the students): (a) A gene is a heritable unit transmitted from parents to offspring [Mendelian concept]. (b) A gene is a sequence of DNA which codes for a functional product, which can be a polypeptide or an RNA [Classical molecular concept]. (c) A gene is a structure which transmits information or instructions for development and organic function from one generation to another [Informational conception]. (d) A gene is a determinant of phenotypes or phenotypic differences [Gene-P]. (e) A gene is a developmental resource, side to side with other equally important resources (epigenetic, environmental) [Gene-D]. (f) A gene is a process that includes DNA sequences and other components, which participate in the expression of a particular polypeptide or RNA product [Process molecular concept]. (g) A gene is any segment of DNA, beginning and ending at arbitrary points on the chromosome, which competes with other allelomorphic segments for the region of chromosome concerned [Evolutionary gene concept, sensu Dawkins]. (h) A gene is a sequence of DNA with a characteristic structure [Classical molecular concept]. (i) A gene is a sequence of DNA with a characteristic function [Classical molecular concept]. (j) A gene is a sequence of DNA containing a characteristic information [Informational conception].

The study was approved by the Research Ethics Committee of the Institute of Collective Health/UFBA and by the National Committee of Research Ethics (recording number 12112), and the participants gave informed consent to participate.

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[17] In both universities, the biology curriculum includes two courses on Genetics and one course on Cell and Molecular biology.

16.3.2.3 Data Analysis

For analyzing the students' responses to the open-ended question, we used the same technique described in the study about textbooks, categorical content analysis, following the same procedures. In the closed questions, we tabulated the frequencies of the alternatives marked in the forced- and free-choice items.

In order to increase internal reliability, two researchers performed independent analyses of the students' answers to the open-ended questions. Inter-rater agreement between these analyses was not very high, reaching 60 %. It was very important, then, to discuss the differences in categorization between those two researchers. This was done by a group of four researchers, including two senior researchers not involved in the previous analyses. We included in the final analysis only those answers for which shared agreement was possible.

The hybrid answers to the open-ended question were recategorized by three researchers who strived for reaching a consensus concerning the prevailing meaning. Once each answer was classified into a single category, they were analyzed statistically through a chi-square test in order to ascertain whether there were significant differences between the views of students who had attended or not the Genetics and Cell and Molecular biology courses. Thus, we could test the influence of the courses on students' ideas about genes in both universities, including also data from the closed questions. The null hypothesis (H_0) was that the two variables would be independent, i.e., the fact that the students had attended the courses would not affect their views about genes and their functions. H_0 would be rejected when the calculated chi-square was equal to or greater than 9.48, and the alternative hypothesis (H_1) would be accepted, showing influence of the courses on students' views. The significance level (α) was 0.05 and for all questions the degree of freedom was equal to 4.

16.3.3 Investigating a Teaching Sequence on the Problem of the Gene

16.3.3.1 Construction of the Teaching Sequence

The study was conducted in two classes of Medicine freshmen students, who attended in the second semester of 2009 the Cell and Molecular biology course under the responsibility of a teacher-researcher involved in the study, at Federal University of Bahia, located in Northeast Brazil. One class (11 students, 18–24 years) followed an approach employed by the teacher for many years, with no explicit discussion about gene function models and gene concepts (hereafter, class A). In another class (13 students, 15–23 years), the new teaching sequence was implemented, including an explicit discussion on those models and concepts, in a modest but explicit approach to the nature of science (NOS) (Matthews 1998; Abd-El-Khalick and Lederman 2000) (class B). Most students came from households with high and middle income.

Table 16.3 Framework proposed by Mortimer and Scott (2003) for the analysis of interactions and meaning making in science classrooms

Analytical aspects	
i. Teaching focus	1. Teaching purposes 2. Content
ii. Approach	3. Communicative approach
iii. Actions	4. Patterns of interaction
	5. Teacher's interventions

The Cell and Molecular biology course is traditionally divided into two modules, molecular and cellular. Usually, the course includes theoretical and practical lessons and students' seminars. Theoretical lessons comprise a short quiz; an activity oriented by a study guide; teacher's exposition, in which he makes the students feel free to pose questions and raise doubts; small group work, in which selected texts are discussed; and whole class discussion. Practical lessons aim at allowing students to observe cell phenomena and offering them an initiation to lab practices. In the seminars, students are divided into small groups to present selected scientific papers.

The teaching sequence was built collaboratively with the teacher, who has B.Sc. in Biological Sciences and M.Sc. and Ph.D. in Pathology. At the time of the study, he had 17 years of experience teaching this same course.

To construct the teaching sequence, we considered three a priori analytical dimensions (Artigue 1988; Méheut 2005): (1) epistemological, related to the contents to be learned, the problems they can solve and their historical genesis; (2) psycho-cognitive, considering the students' cognitive characteristics; and (3) didactic, linked to the constraints posed by the functioning of the teaching institution (programs, timetables, etc.). The first dimension followed from the historical and philosophical background used in the research program. The second benefited from the collaboration with the teacher, who has a wealth of knowledge on students' previous conceptions, difficulties, etc. Finally, we deliberately constructed the teaching sequence to be compatible with the typical constraints involved in undergraduate Cell and Molecular biology courses, which typically have extensive syllabi in Brazilian universities, with much content to be covered usually in 45–60 h. We planned the teaching sequence to fit into the time made available by the teacher, 5 h distributed in 2 days of classes. Within these time constraints, he assured us, it would be more feasible that the proposal could be used in most similar courses.

We used a discourse analysis perspective to plan the activities, designing communicative approaches and interaction patterns to be used by the teacher. The framework for classroom discourse analysis developed by Mortimer and Scott (2003) was adapted for this goal. It is based on five interrelated aspects that focus on the teacher's role, grouped in three dimensions: *teaching focus*, *communicative approach*, and *actions*. The *communicative approach* is the central element, since it is through it that we understand how the teaching focuses are worked, i.e., the *teaching purposes* and *contents*, by means of which actions, the *pedagogical interventions*, which result in certain *patterns of interaction* (Table 16.3).

The investigation was framed in the context of educational design research (Baumgartner et al. 2003; Plomp 2009; van den Akker et al. 2006), which aims at both developing educational interventions and advancing our knowledge about their characteristics and the processes of designing and developing them. The main research question in educational design research is to establish what are the characteristics or design principles of an intervention X for obtaining the outcome $Y(Y_1, Y_2, \ldots, Y_n)$ in context Z (Plomp 2009). Design principles are initially derived by us from the relevant literature and practitioner knowledge, and as the investigation of a series of prototypes of the teaching sequences proceeds, we not only test the initial design principles but also derive additional principles from the empirical results.

At this point, we tested just the first prototype of the teaching sequence in a single classroom. The following design principles were used: (1) The classroom discursive interactions were planned to flow from a dialogical approach, in which students' ideas played a prominent role in meaning making, to a more authoritative approach, in which the diversity of ideas raised was subjected to evaluation and selection in order to construct in the classroom the perspective of school science; (2) in classroom discursive interactions, the teacher stressed key ideas when they appeared, in order to construct the school science perspective around them; (3) texts produced by ourselves, aiming at the didactic transposition of debates on genes and their functions, were provided to small groups of students, alongside with guiding questions; (4) the teaching sequence used a historically and philosophically informed approach, putting emphasis on the role of models in science, their relation with reality, and the importance of their demarcation; (5) several historical models of gene function and gene concepts were explicitly addressed and differentiated; (6) the crisis of the classical molecular concept was explicitly discussed, as well as reactions to it; (7) in order to discuss this crisis, the teacher used molecular phenomena already addressed in his classes previously, even though at that point no conceptual consequences related to genes were derived.

16.3.3.2 The Teaching Sequence

The teaching sequence adopted an explicit approach to the NOS in the context of teaching about genes and their function, seeking to promote learning *with* models and *about* models.

The first class begins with the teacher asking the students what is a gene, an open-ended and divergent question intended to raise as many students' conceptions as possible. The teacher avoids evaluative comments or gestures, in order to maintain the dialogical interaction with the pupils. As the students offer their answers, the teacher copies them in the blackboard to be used later. This activity is followed by an exposition about models and their role in science. Even though the teacher speaks most of the time, he prompts the students to participate by posing questions. The students are divided into small groups and receive the first text prepared by our team, "historical models of the gene concept" (text contents are similar to those found in Sect. 16.2 above), followed by a number of guiding questions for cooperative discussion. The answers are used by the teacher to promote whole class discussion, which creates the opportunity to prompt sharing of the discussions in the small groups, to check the students' understanding and to stress key ideas for the construction of the intended perspective on genes. He goes back then to the students' initial answers, available in the blackboard, discussing the relationship between their ideas and the historical models about gene function. Now he evaluates their answers, showing when they are closer to one or another model and pointing out which models are still accepted and in what features. He also stresses which answers are distant from any scientific model and brings to the fore the hybrid models, if they are present in the students' answers. The expectation is that, at the end of the class, the diversity of students' ideas raised and the diversity of scientific models about genes have been systematized.

In the second class, the teacher begins by briefly reviewing the previous session and posing questions for the students in order to evaluate their understanding. Then, he makes an exposition on the crisis of the classical molecular concept, using challenging phenomena that were already discussed in the previous classes, such as alternative splicing and gene overlapping. The students are divided again into small groups, receiving the second text we prepared, "proposals for the gene concept" (text contents are similar to those in Sect. 16.2), with guiding questions. Again, this is followed by whole class discussion. The class ends with a discussion on the current status of our understanding about genes, in which the teacher highlights the idea that the classical molecular concept is in crisis, but none of the proposals discussed in the second text are widely accepted by the scientific community. The intended perspective on genes is arguably clear for the students: the gene concept is now changing under our very noses, with all directions of change still being debated. The teacher also takes a last opportunity to stress the existence of a diversity of gene concepts and models of gene function, claiming that several models show greater explanatory and heuristic powers than a single, overarching definition of gene, provided that we properly demarcate their domains of application.

16.3.3.3 Teaching Sequence Validation

We performed a posteriori internal and external validation of the teaching sequence (Artigue 1988; Méheut 2005). In the internal validation, we compared the effects of the teaching sequence in relation to its goals, by comparing the students' learning outcomes with the planned learning goals. To perform this comparison, we investigated how the students mobilized ideas about genes and their function in a discursive context structured by a subset of the items from the questionnaire used to investigate students' views (see above), with some modifications validated in a pilot test. Here we will discuss the same three questions mentioned above. In the closed questions, the alternative (g), related to the evolutionary gene concept, was excluded in this study. The questionnaire was used in three moments: in the second lesson of the whole course, when we could probe students' views with no influence of the course (pretest); at the end of the molecular module, which coincided with the last day of the teaching sequence (posttest); and two months after the intervention (retention test). The classes have also been video recorded to provide raw material for the analysis of classroom discursive interactions, but these data have not been treated yet.

In the internal validation, we are evaluating if the teaching sequence does reach the planned learning goals. If we use the framework presented by Nieveen et al. (2006), this is a development study, aiming at solving educational problems by focusing on the proposal and testing of broadly applicable design principles. The goal is to understand how and why a given intervention functions in the particular context in which it was developed. It is this knowledge that is summarized in design principles (Reeves 2006; van den Akker et al. 2006), or intervention or design theories (Barab and Squire 2004), which are expected to generalize beyond the context of the study. Although we cannot expand further on the topic here, we should mention that this knowledge is conceived by us as generalizing in two (not mutually exclusive) ways: (1) through situated generalization (Simons et al. 2003), i.e., the transformation of data gathered in a context into evidence transferable to other contexts, so as to indicate a course of action or be incorporated in judgments preceding action, due to teachers' perception of a connection between the investigated context and the context of their pedagogical work, and (2) as a generalization resulting from maximizing the variation of qualitatively different investigated cases (Larsson 2009). As we investigated only the first prototype of the teaching sequence, the second kind of generalization is not yet at reach. However, the first kind of generalization is already feasible, since other college and university teachers may perceive the same problems discussed here in their classrooms and, eventually, see in the teaching sequence a putative approach to their pedagogical practice.

We also performed a *preliminary* external validation of the sequence by comparing the effects of the teaching sequence with the approach employed for many years in the course. The same questionnaire was applied for class A in the same moments mentioned above. Using Nieveen and colleagues' (2006) framework, this is an effectiveness study, which can provide evidence for the impact of the intervention by comparing its effectiveness in relation to another teaching approach. As Brown (1992) argues, our goal in such a study should be to accommodate variables rather than controlling them, since research needs to occur within the natural constraints of real classrooms. One manner of accommodating confounding variables is to use sufficient numbers of replicas of each treatment such that we can distinguish between the effects of the intervention and confounding variables randomly assorted to the replicas, such as students' motivation, the quality of their previous knowledge, and teacher-students relationships. But when we do research in real educational contexts, we often do not count with enough number of classes for replicating treatments. This was the case in our study, since there was only one teacher interested in engaging in it, and he had only two courses under his responsibility. This means that we cannot sufficiently distinguish between the effects of the teaching sequence and confounding variables, although we had the same teacher and similar sets of students in the two classes. Nevertheless, the results revealed interesting patterns, although preliminary and to be taken with a grain of salt.

16.3.3.4 Data Analysis

The answers to the questions included in the tool were treated through categorical analysis (open-ended item) and tabulation (closed item) as described above. Internal reliability was increased in the open-ended question by independent analyses by two researchers, with high inter-rater agreement (89.1 %). Differences in categorization were discussed with two other researchers (one of them also the teacher of the course), and the final analysis included only those answers in which shared agreement was reached.

16.4 Results and Discussion

16.4.1 Textbook Studies

16.4.1.1 Views About Genes in Higher Education Cell and Molecular Biology Textbooks

Figure 16.1 shows the distribution of gene concepts in the three higher education Cell and Molecular biology textbooks we analyzed (Pitombo et al. 2008).

In Karp's (2004) textbook, there were 73 recording units explicitly addressing gene concepts, considerably more than in the other two books (35, Alberts et al. 2002, 23, Lodish et al. 2003). This follows from the fact that the former book focuses on concepts and experiments, as shown by its subtitle, giving more attention to history. Symptomatically, the Mendelian conception, according to which the gene is a unit of inheritance, showed the highest prevalence (31.5 %), and most of these occurrences were in sections discussing the history of genetics. The Mendelian conception is mostly treated in this textbook as a view on genes that is historically relevant, but is not often used to account for current perspectives on genes, which are frequently represented by the second most frequent view (24.6 %), the informational conception, in which the gene is seen as a unit or carrier of information. Since information is a metaphorical notion that still needs theoretical clarification in genetics (El-Hani et al. 2009; Griffiths 2001), it is problematic to appeal mainly to this idea to explain what genes are. The third more frequent concept in Karp was gene-P (20.5 %), which was mostly used in sections about the history of genetics and medical genetics, where it usefully abstracts away from the complexities of the genotype-phenotype relationship, focusing on the predictive relationship between gene loci and pathological conditions. Finally, the classical molecular concept appeared in 13.7 % of the recording units, distributed in a wide variety of contexts, including molecular biology, evolutionary genetics, genetic engineering, and genomics, besides historical narratives about genetics. We can say, therefore, that in this textbook, when genes are described in molecular terms and from an updated perspective, the molecular-informational model of gene function prevails.

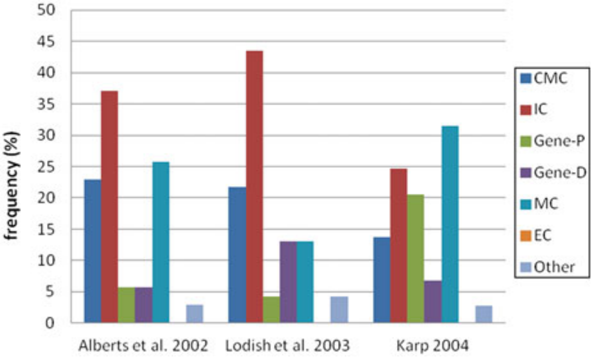

Fig. 16.1 Distribution of gene concepts in three higher education Cell and Molecular biology textbooks. *CMC* classical molecular concept, *IC* informational conception, *MC* Mendelian conception, *EC* evolutionary concept

Alberts et al. (2002) and Lodish et al. (2003) are much less diversified in their treatment of genes, even though they still show conceptual variation. In these textbooks, the informational conception was remarkably predominant (37.1 %, Alberts et al.; 43.5 %, Lodish et al.), being frequently associated with the classical molecular concept (22.9 %, Alberts et al.; 21.7 %, Lodish et al.). Their basic message about the nature of genes amounts, thus, to a combination of the metaphor of information and the idea of the gene as unit of structure and/or function in DNA, which is characteristic of the molecular-informational model.

In all the textbooks, the classical molecular gene concept was predominantly used when they were addressed contents related to Molecular biology and Molecular Genetics. This concept was also used by the three textbooks in their glossaries, in order to define genes. The informational conception, in turn, was found in more diversified contexts in the textbooks, when compared with the classical molecular gene concept, indicating how widespread this conception is, despite its lack of solid theoretical background.

However, the prevalence of the molecular-informational model sounds strange in the three textbooks, when we consider that they discuss the anomalies challenging it in the last decades. The conceptual lessons following from these empirical findings are not taken into account, yet another indication of a largely atheoretical and ahistorical treatment of the contents. Despite the presence of conceptual variation, these textbooks do not provide clues for teachers and students about the distinct origins, domains of application, and meanings of concepts related to different models along the history of genetics and molecular biology. Thus, hybridization of incommensurable aspects of different models and semantic confusion are likely to happen. This is a good case in point regarding the harmful consequences of teaching science without teaching about science. The students do not have much chance of learning with models and about models, since these textbooks address the contents as if they referred to reality themselves, as discovered by science, not to models about reality, historically constructed by the scientific community. The relationship between model and reality becomes unclear when most of the explanations just consider what *is* in the world, not how we interpret what *is* in the world based

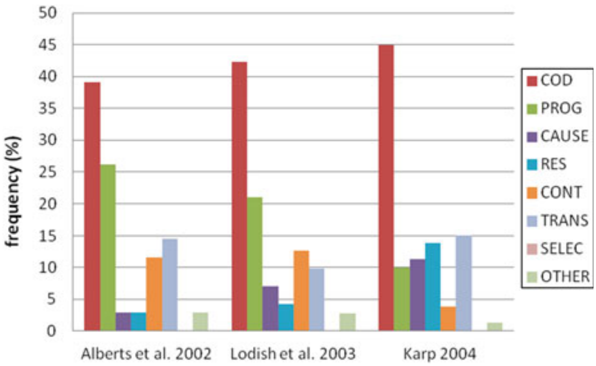

Fig. 16.2 Distribution of functions attributed to genes in three higher education Cell and Molecular biology textbooks. *COD* codifying the primary structure of polypeptides or RNAs (classical molecular concept), *PROG* program or instruct cellular functioning and/or development (informational conception), *CAUSE* cause or determine phenotype or difference between phenotypes (gene-P), *RES* act as a resource for development (gene-D), *CONT* control cell metabolism (informational conception), *TRANS* transmit hereditary traits (Mendelian conception), *SELEC* act as unit of selection (evolutionary concept)

on theoretically laden evidence and inferences (which are often conflated in the textbooks with observations).

As an example, the following definition hybridizes features related to the Mendelian and the informational conception:

> Gene - Physical and functional unit of heredity, which carries information from one generation to the next (Lodish et al. 2003, Glossary, G-9).

This sentence, in turn, hybridizes gene-P and the informational conception:

> These instructions are stored within every living cell as its genes, the information-containing elements that determine the characteristics of a species as a whole and of the individuals within it (Alberts et al. 2002, p. 191).

The harmful consequences of combining these different features of historical models become apparent, as the idea of "genetic information" is taken to imply a reduction of the development of all characteristics of the species and the individuals to the DNA nucleotide sequences. We can explicitly see the connection between the genetic determinism that often marks gene talk in the social arena and the way genes are treated in these textbooks.

The interpretation that the molecular-informational model prevails in these textbooks is reinforced when we examine the functions attributed to genes (Fig. 16.2). In all of them, the function most frequently ascribed is codifying the primary structure of polypeptides or RNAs, aligned with the classical molecular concept (39.1 %, Alberts et al.; 42.3 %, Lodish et al.; 45 %, Karp). In the former two textbooks, the second most frequent function, to program or instruct cellular function and/or development, is also related to that model, namely, to the informational conception (26.1 %, Alberts et al.; 21.1 %; Lodish et al.). In Karp, to transmit hereditary traits is the second most common function (15 %), consistently with the high prevalence of the Mendelian conception.

Generally speaking, we observe a proliferation of meanings attached to genes as we progress from context to context in these textbooks, with no model unification or demarcation. This happens both in gene concepts and function ascription to genes.

16.4.1.2 Views About Genes in High School Biology Textbooks

Figure 16.3 shows the distribution of gene concepts in 18 Brazilian high school biology textbooks, including those approved and not approved by the Brazilian National Program for High School Textbooks (PNLEM) (Santos et al. 2012).

In these textbooks, three gene concepts were significantly more prevalent: the classical molecular concept, the informational conception, and the gene-P. In 12 of the 18 textbooks, gene-P was the most frequent, answering for more than 40 % of the recording units in 4 textbooks. The classical molecular concept and the informational conception were more prevalent in 3 textbooks each.

The fact that gene-P is so often used in these textbooks follows from the extensive content of the genetics chapters, where we find several examples of pedigree analyses and estimates of the inheritance probability of phenotypic traits. Here is an example of a recording unit showing gene-P:

> The gene for brown eyes located in the chromosome is an allele of the gene for green eyes, located in the homologous chromosome (T2, vol. 3, p. 15).[18]

Gene-P is often employed in the textbooks just as it was used in classical genetics, when genes were inferred from phenotypes. However, these statements are framed in an "updated" language, and thus, teachers and students cannot figure out that the textbook is using a way of understanding genes that was frequently employed when there was no established knowledge on the nature of the genetic material. Moreover, a key requirement for a valid usage of genes-P is not found in these textbooks, namely, a clear understanding of the distinction between this instrumental concept and a realist interpretation of the genetic material. In the absence of this distinction, gene-P is simply conflated with the classical molecular gene concept, which provides then a molecular background to understand genes as determinants of phenotypes, as expressed by gene-P. The kind of conflation that Moss (2001, 2003) identifies as a source of genetic determinism, between a preformationist instrumental concept (gene-P) and a molecular realist concept (gene-D), is favored by the way these textbooks deal with genes.

It is this sort of hybridization between features related to different models that can lead to semantic confusions, hampering students' understanding and favoring ideas with important socioscientific implications, such as genetic determinism. If a student learns that genes determine phenotypes in the absence of a historically and

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[18] All translations of textbook passages from Portuguese were made by the authors of the present paper. Commentaries by the authors are shown in brackets.

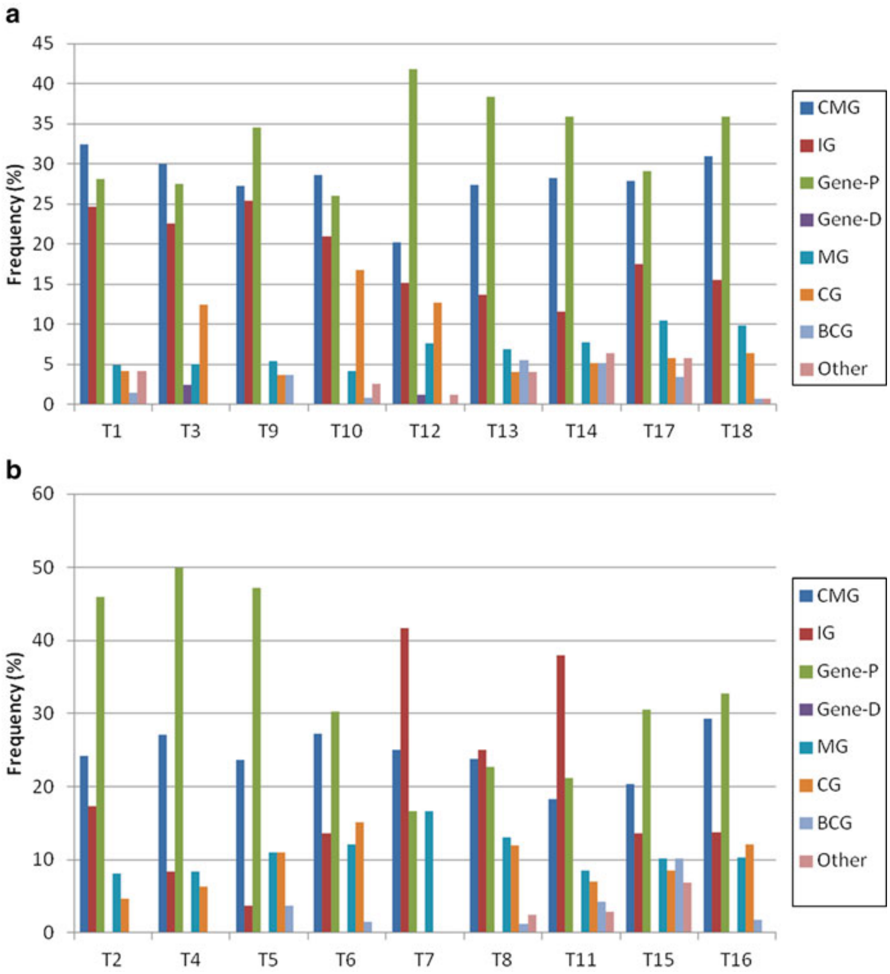

Fig. 16.3 Distribution of gene concepts in Brazilian high school biology textbooks. *CMG* classical molecular gene, *IG* informational gene, *MG* Mendelian gene, *CG* classical gene, *BCG* biochemical-classical gene. (**a**) Textbooks approved; (**b**) textbooks not approved by PNLEM. Textbooks are indicated by the codes listed in Appendix 1

epistemologically informed discussion of the role of this instrumental concept in classical genetics and then moves on to study about genes depicted in a realist manner as structural and functional units in DNA, the conflation between these two concepts and the resulting semantic confusions seem almost inevitable.

Symptomatically, in all textbooks in which gene-P prevails, the second most frequent concept was the classical molecular gene. Moreover, in 39.1 % of the recording units where we found the classical molecular gene, gene-P was also present. The classical molecular concept only entails colinearity between a gene and the primary structure of a protein or RNA but does not fix the relationship between genes and phenotypes at a higher level. This relationship enters the textbook explanation through the hybridization with gene-P, predictably leading to genetic determinism. The passage below illustrates the hybridization between the classical molecular gene and gene-P, with clear determinist undertones:

> Currently we know that the gene [...] is a sequence of nucleotides in DNA. Each gene is responsible for the synthesis of a protein and, consequently, for one or more characteristics of the individual, since proteins can have structural and regulatory functions in metabolism. Genes are located in chromosomes and are didactically represented by letters, numbers, and symbols. For instance, the gene for normal skin color is symbolized by *A* and the gene for albinism, by *a* (T6, p. 283).

This amalgam of a preformationist view of the gene as determinant of phenotypes and a molecular view of the gene as information carrier located in DNA is the major picture of the gene in these textbooks. The classical molecular concept, in particular, was found in the most diverse contents in the textbooks, in all three high school years, with relatively high frequency (Santos et al. 2012).

In Fig. 16.4, we can see the functions attributed to genes in the high school biology textbooks we analyzed. In almost all textbooks (17), genes are most often regarded as codifiers of the primary structure of polypeptides or RNAs (in accordance with the classical molecular concept) and determinants of phenotypes (in line with gene-P).

All the historical models identified by Gericke and Hagberg (2007) were found in the textbooks (Fig. 16.5), showing how they are marked by conceptual variation. The molecular-informational model was dominant, in keeping with the prevalence of the classical molecular concept and the informational conception in the textbooks. However, the difference of prevalence between the four most frequent models is in fact quite small, highlighting how the predominant feature of these textbooks is, in fact, conceptual variation, with no clear demarcation between the different models and their domains of application. Gericke and colleagues (in press) compared the distribution of these historical models in a large and significant sample of Swedish and Brazilian textbooks, as well as in 7 textbooks used in English-speaking countries. Despite some differences, the distribution of the different models within the textbooks of the different countries was very similar. They interpret this finding as showing that the conceptual variation in genetics is captured in a similar textbook discourse that is culturally independent, that is, didactic transposition (Chevallard 1989) leads to similar end products in those different countries, maybe as a consequence of the influence of the higher education textbooks used by textbook authors to learn about genetics and cell and molecular biology.

Half of the high school textbooks analyzed (9) discussed split genes. To our understanding, six of them treated split genes and splicing in a satisfactory manner. However, only three considered alternative splicing, and among the latter, only two discussed the conceptual implications of this phenomenon to the way genes are conceived.[19] This indicates that, in spite of the overwhelming predominance of an outdated

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[19] It is worth noting, however, that none of the higher education cell and molecular biology textbooks offered such a discussion.

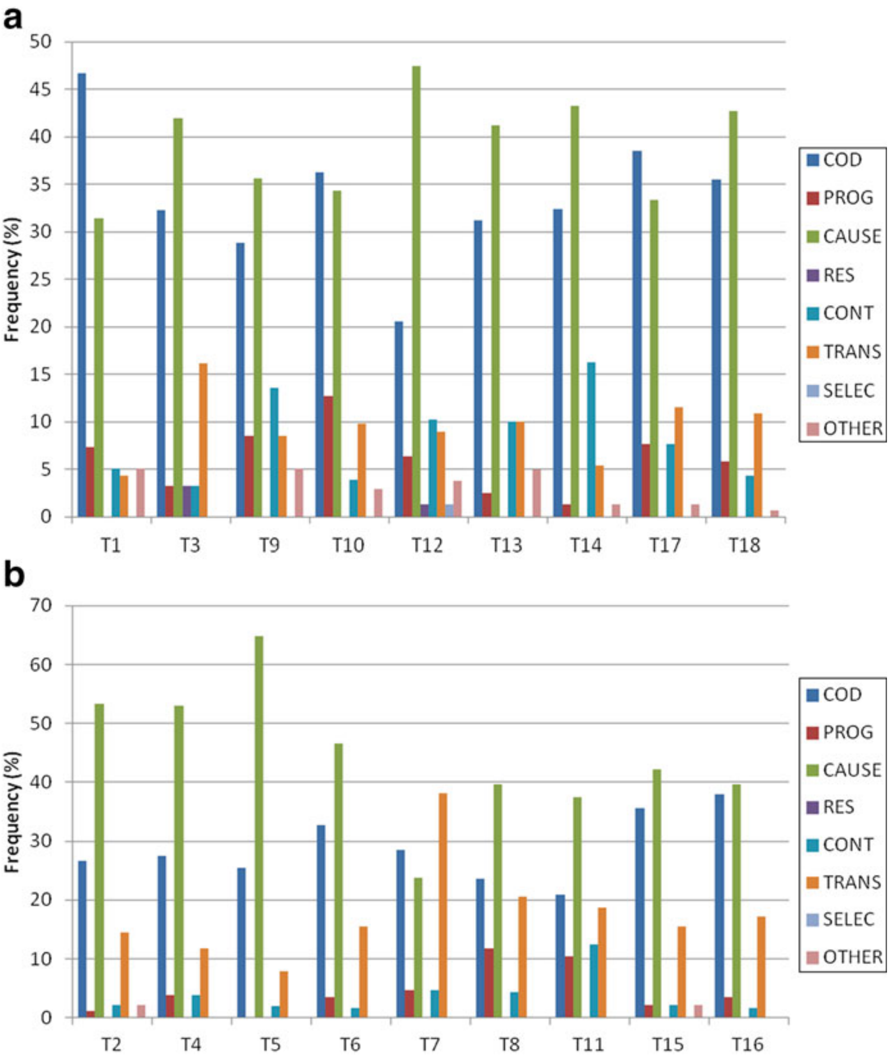

Fig. 16.4 Distribution of functions attributed to genes in Brazilian high school biology textbooks. *COD* codifying the primary structure of polypeptides or RNAs (classical molecular concept), *PROG* program or instruct cellular functioning and/or development (informational conception), *CAUSE* cause or determine phenotype or difference between phenotypes (gene-P), *RES* act as a resource for development (gene-D), *CONT* control cell metabolism (informational conception), *TRANS* transmit hereditary traits (Mendelian conception), *SELEC* act as unit of selection (evolutionary concept). (**a**) Textbooks approved; (**b**) textbooks not approved by PNLEM. Textbooks are indicated by the codes listed in Appendix 1

approach to the gene concept, at least in some textbooks, there seems to be an ongoing transition to a more updated treatment. However, in the majority of the high school textbooks, the case is similar to that of higher education textbooks: when the challenges to the classical molecular concept are discussed, relatively

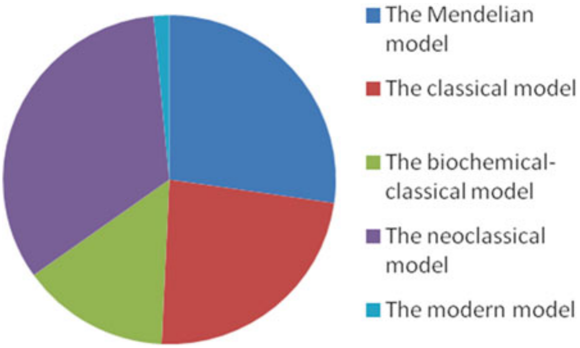

Fig. 16.5 Distribution of the historical models identified by Gericke and Hagberg (2007) in Brazilian high school biology textbooks (in percentage)

obvious conceptual consequences are not considered. This can be seen as a consequence of the way the textbooks typically approach scientific knowledge, as a list of isolated facts, building a fragmented rhetoric of conclusions (Schwab 1964).

When using the vast majority of these textbooks, students and teachers cannot get even a glimpse of the state of affairs in current discussions about genes. Some may think that it is too much to demand that school science considers these recent developments at high school. However, for most students this may be the last opportunity to learn about genes and their function and, thus, to build a critical stance towards gene talk in socioscientific issues, from the safety of genetically modified organisms to the use of genetic testing in society.

We also did a systematic analysis of model hybridization in the high school biology textbooks, finding a widespread use of hybrid models for describing gene function (Table 16.4), often combining features of models focusing on the molecular and cellular level with features of models dealing with the phenotypic level, derived from classical genetics. As Santos and colleagues (2012) show, the molecular-informational model seems to be taken as a basis by the textbooks, with features from a variety of models being hybridized with it. Thus, conceptual variation, although present in the textbooks, is not explicitly dealt with, being difficult for teachers and students to realize that different aspects of gene function are mixed up and, in particular, to take notice of the ambiguities, logical inconsistencies, and semantic confusions that may follow.

16.4.2 Higher Education Students' Views About Genes and Their Functions

The Biological Sciences students who participated in the study about their views about genes and their functions were divided into two groups, depending on whether they attended (YG) or not (NG) Genetics courses. In one of the universities investigated, located at the South part of Brazil (UFPR, U1), the distribution was 32 students in group YG and 28 in NG. In another university included in the study,

Table 16.4 Hybridization frequency of textbook models

	Mendelian model	Classical model	Biochemical-classical model	Molecular-informational model	Modern model
Level of hybridization (%)[a]	7.7	18.4	9.5	41.8	

[a] The level of hybridization equals the frequency of exchanged epistemological feature variants, calculated as the number of incorrect historical feature variants (nonhistorical and false historical) divided by the total number of feature variants in the textbook models

located in the Northeast region of Brazil (UFBA, U2), we had 19 students in YG and 33 in NG.

The chi-square test performed to statistically analyze the influence of the Genetics course on students' ideas about genes in both universities resulted in the values 9.83 and 10.07 in U1 and U2, respectively. Thus, in both universities, a significant relationship was found between the students' attendance to the Genetics courses and the views about genes expressed in their answers.

Figure 16.6 shows the distribution of the answers in the categories obtained in the analysis of the open-ended and divergent question "In your view, what is a gene?" for the two universities and the two groups.

Regarding the classical molecular concept and the informational conception, the results show similar effects of the Genetics courses on Biological Sciences students' views in the two universities. They led to a significant increase in the percentage of answers committed to the classical molecular concept and a decrease in the students' commitment to the informational conception, with the difference that only a slight decrease took place at U1.

On the one hand, if we consider that basically all the challenges faced by the classical molecular concept are addressed by those courses, we can suspect that no connection is made between examining empirical findings in genetics and cell and molecular biology and reflecting on their conceptual implications. This may be a consequence of the lack of an epistemological and historical dimension in the teaching practice in those courses. On the other hand, the impact they had on the students' appeal to the informational conception is a positive consequence of the courses, which can be attributed to the fact that the students are stimulated to delve into more details regarding the structure and function of the genetic material. This can be associated to both the increase in their allegiance to the classical molecular concept and the decrease in their use of the informational conception.

As an example of a student's answer committed to the classical molecular concept, we can quote[20]:

> It is a fragment of DNA responsible for codifying a polypeptide chain or RNA (U1, student 20, YG).

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[20] The answers were freely translated from Portuguese to English by the authors of the paper.

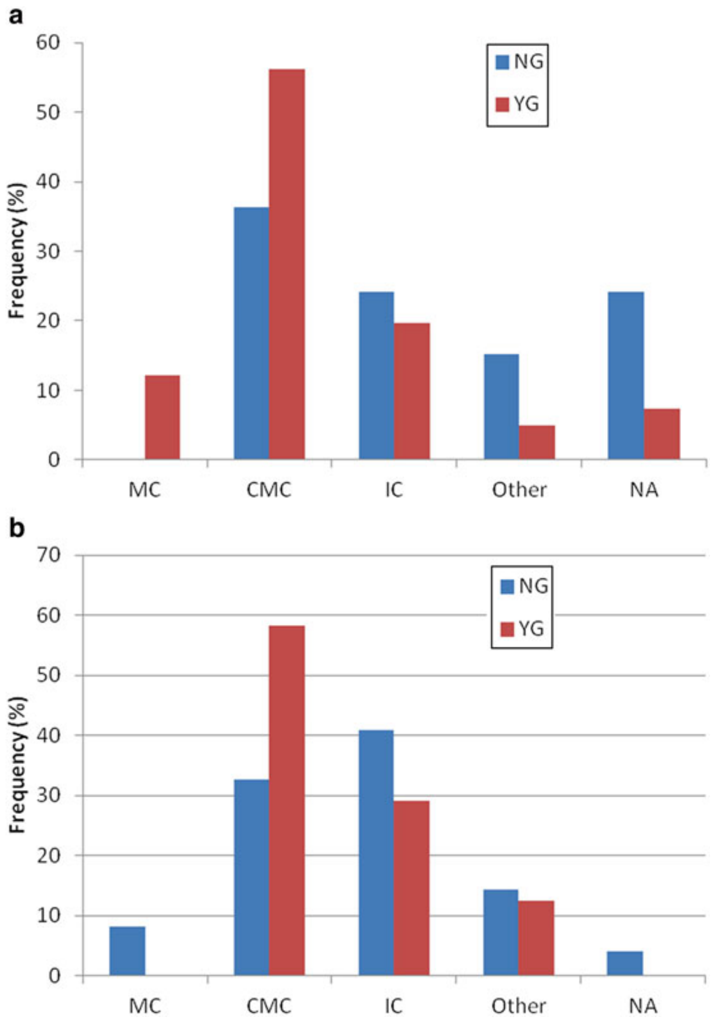

Fig. 16.6 Distribution of answers given by students of two Brazilian universities to the question "In your view, what is a gene?" *MC* Mendelian conception, *CMC* classical molecular concept, *IC* informational conception. (**a**) U1 (UFPR); (**b**) U2 (UFBA). The number of answers is larger than the number of students because there were answers which combined more than one view about genes and, thus, were classified in more than one category

Here is an example, in turn, of an answer exhibiting the informational conception:

> Hereditary informational unit (U1, student 3, YG).

Different views about genes were often hybridized by the students in their answers (21.7 % of the answers in U1, 38.5 %, in U2). This suggests that the students may be reproducing the hybrid views about genes found in textbooks (see

Sect. 16.4.1). As there was no trend of decrease of such hybridization after the Genetics courses, classroom teaching and learning seems to be unable to overcome this difficulty posed by the treatment of genes and their functions in the textbooks.

In the closed questions, we used the classification of the alternatives into gene concepts shown in the methods section and, additionally, gathered less represented answers, related to gene-P, gene-D, and the evolutionary gene concept, into a single category, other gene concepts. When considering the forced-choice question, we can see the same pattern observed in the open-ended question regarding the prevalence of the classical molecular concept (particularly, item b, Fig. 16.7. In items h and i, also related to this concept, there were no important changes) and the decrease of the informational conception (items c and j, Fig. 16.7) after the students attended the courses.

In both universities, the students' commitment to the Mendelian conception, as shown by the closed questions, decreased (item a, Fig. 16.7). This may be a consequence of the impact of the molecular treatment of genes during the courses.

Now, compare Fig. 16.7 with Fig. 16.8, which shows the results for the very same closed question, but in a free-choice format. The pattern that is readily apparent is that the students marked a large variety of views about genes when they are allowed to do so. To our understanding, this is a striking evidence that conceptual variation regarding genes, as represented in higher education and high school textbooks, can be translated into students' allegiance to several different accounts about genes and their functions. In itself, the results from these two questions do not allow us to conclude that students are facing difficulties with this conceptual variation, for instance, not knowing what views about genes are more adequate to deal with what sorts of problems, or being entangled in semantic confusions and ambiguities following from combining incommensurable perspectives embraced by different models and concepts. But consider that teaching about genes in those courses uses the textbooks we analyzed, where a historically and epistemologically informed approach to models about genes and their function is typically lacking. It is at least plausible, then, to interpret the fact that the students marked so many different views about genes in the free-choice question as meaning that they are prone to conflate incommensurable aspects of models and, also, to misapply these models, using them outside their domain of validity.

16.4.3 From Diagnosis to Intervention: A Teaching Sequence on the Problem of the Gene

Our previous study on higher education students' views about genes and their functions suggested several shortcomings in teaching about genes at Genetics courses in two Brazilian universities. Part of the limitations of these courses could be attributed to the lack of an epistemological and historical dimension in the treatment of the contents, in particular, to an insufficient attention to teaching both *with* models and *about* models (Gericke and Hagberg 2007).

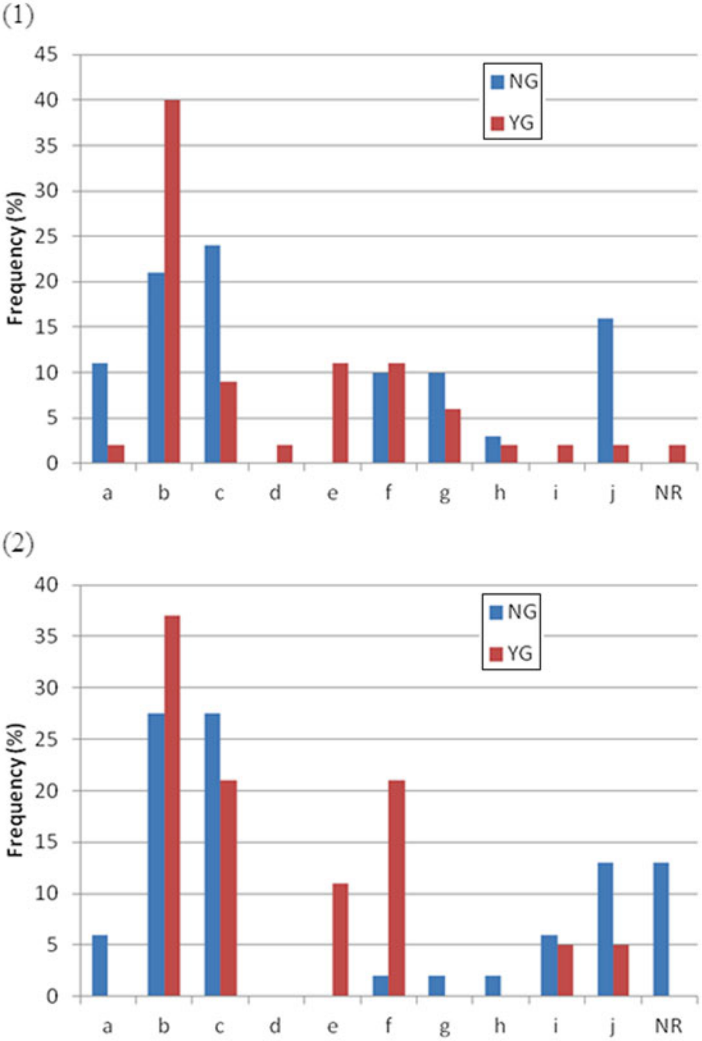

Fig. 16.7 Distribution of answers given by students of two Brazilian universities to a forced-choice closed question presenting several alternatives concerning the nature of genes: (**a**) Mendelian; (**b**), (**h**), and (**i**) classical molecular; (**c**) and (**j**) informational; (**d**) gene-P; (**e**) gene-D; (**f**) process molecular gene; (**g**) evolutionary gene concept. *NR* no response. (1) U1 (UFPR); (2) U2 (UFBA)

Therefore, it seemed natural to us to move from diagnosis to intervention, through the development and investigation of a teaching sequence built collaboratively with a higher education Cell and Molecular biology teacher at the Federal University of Bahia, located in Northeast Brazil. As presented in the Methods section, this teaching sequence explicitly addressed NOS contents, in particular, the historical construction and nature of gene function models and gene concepts. Our intention

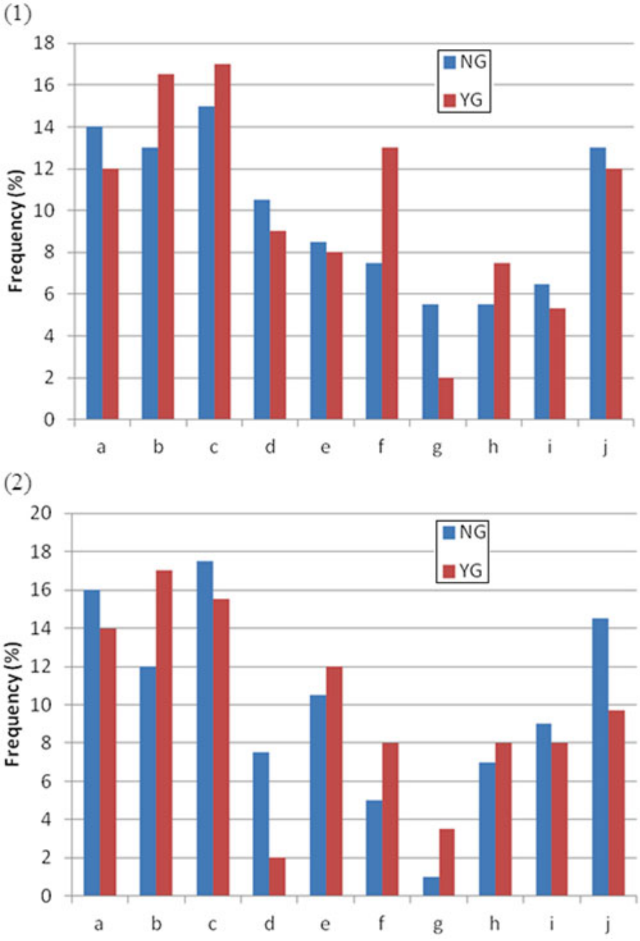

Fig. 16.8 Distribution of answers given by students of two Brazilian universities to a free-choice closed question presenting several alternatives concerning the nature of genes: (**a**) Mendelian; (**b**), (**h**), and (**i**) classical molecular; (**c**) and (**j**) informational; (**d**) gene-P; (**e**) gene-D; (**f**) process molecular gene; (**g**) evolutionary gene concept. (1) U1 (UFPR); (2) U2 (UFBA)

was not to deal with complex historical, philosophical, or sociological issues, but just to teach with models and about models when dealing with genes, as a way of providing conditions for the students to understand that genes have been and are still conceived in different ways in distinct subfields of biology, as a consequence of different epistemic practices that characterize the works of diverse scientific communities.

Figure 16.9 shows the distribution of the answers in the categories obtained in the analysis of the open-ended question "In your view, what is a gene?" in the three

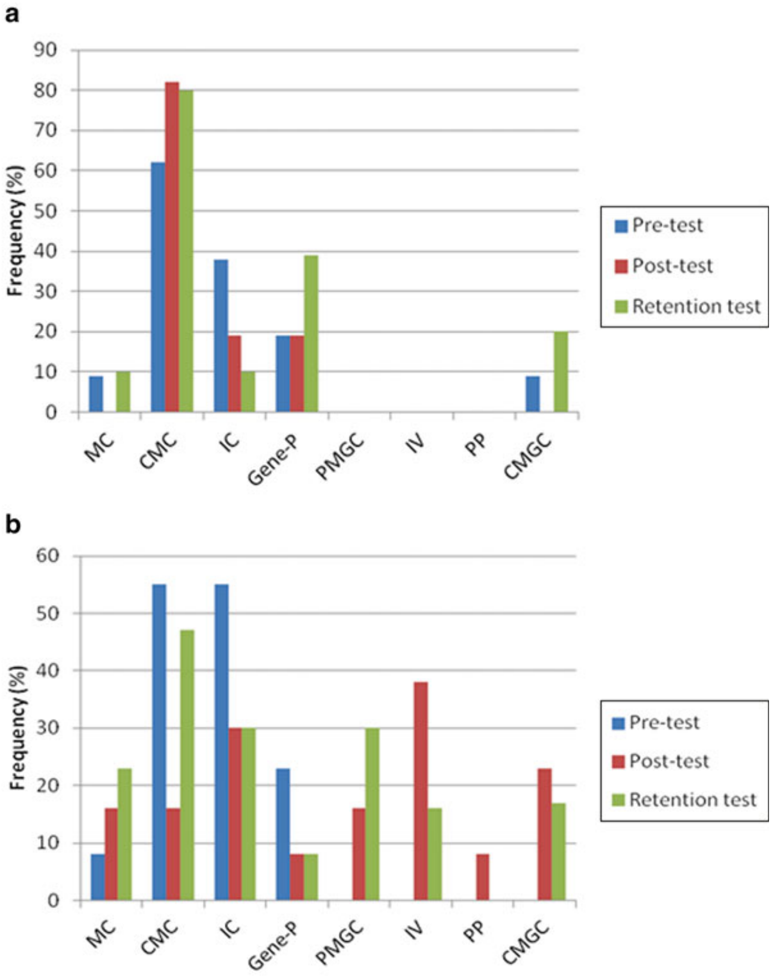

Fig. 16.9 Distribution of answers given to the question "In your view, what is a gene?" by the students of the classes investigated. *MC* Mendelian conception, *CMC* classical molecular concept, *IC* informational conception, *PMGC* process molecular gene concept, *IV*, instrumental view about genes, *PP* perception of the problem, *CMGC* contemporary molecular gene concept (The "contemporary molecular gene concept" amounts to a conservative response to the problem of the gene, which regards the gene as a linear DNA sequence but abandons the idea that it has a single developmental role, defining it, for instance, as "a DNA sequence corresponding to a single 'norm of reaction' of genes products across various cellular conditions" (Griffiths and Neumann-Held 1999, p. 658)). (**a**) Class A (usual approach to the course, with no explicit discussion on gene function models and gene concepts); (**b**) class B (where the teaching sequence was implemented). The number of answers is larger than the number of students because there were answers which combined more than one view about genes and, thus, were classified in more than one category

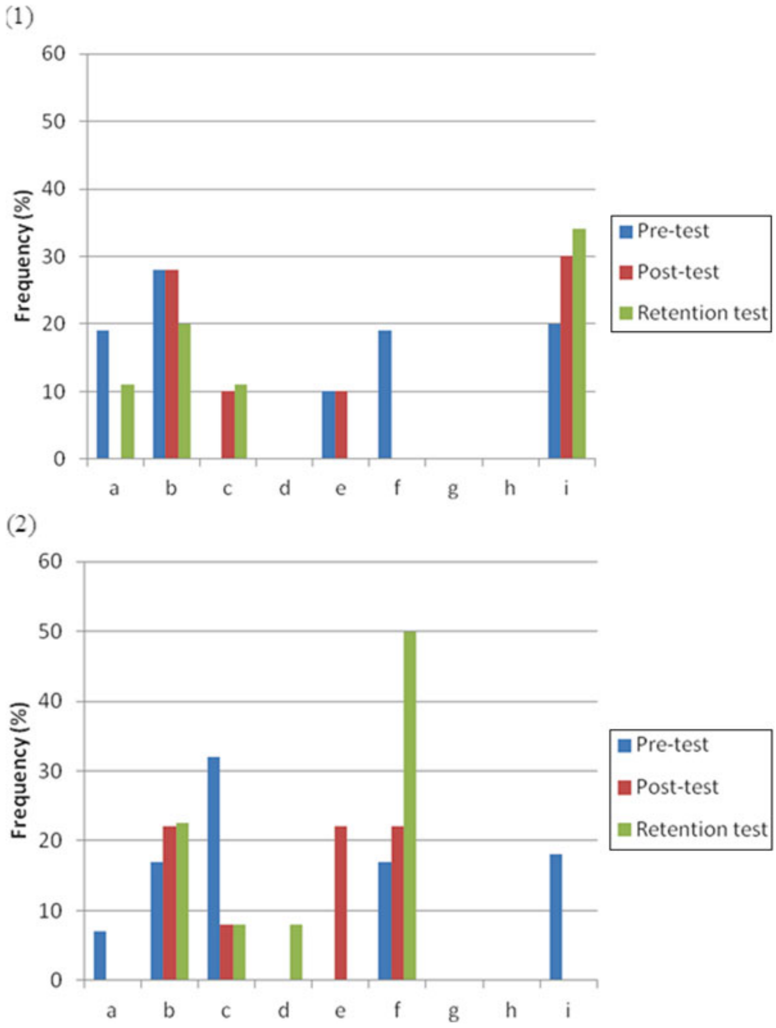

Fig. 16.10 Distribution of answers given by the students of the classes investigated to a forced-choice closed question presenting several alternatives concerning the nature of genes: (**a**) Mendelian; (**b**), (**g**), and (**h**) classical molecular; (**c**) and (**i**) informational; (**d**) gene-P; (**e**) gene-D; (**f**) process molecular gene. (1) Class A (usual approach to the course, with no explicit discussion on gene function models and gene concepts); (2) class B (where the teaching sequence was implemented)

moments in which the data were gathered. It is interesting to look at these results alongside with those for the closed forced-choice question, which allowed us to survey students' ideas about genes using a different kind of tool. We can see the distribution of answers in the pretest, posttest, and retention test in Fig. 16.10.

Considering, first, the internal validation of the teaching sequence, we can see some positive learning outcomes, compared to the intended learning goals: first, the informational conception was successfully challenged by the teaching sequence, falling in the posttest and maintaining the lower frequency in the retention test, when compared with the pretest, both in the open and in the closed forced-choice question. Here is an example of a students' answer committed to the informational conception and, also, showing a close relationship between this conception and genetic determinism:

> Gene is the unit of data storage of the species. The union of the genes (which are in DNA) forms the genome, where we find all the information for the development of the being (Student 2, Class B, pre-test).

Second, the students showed an enriched repertoire of views about genes after the intervention. For instance, the process molecular gene concept increased in frequency in the posttest, reaching an even higher frequency in the retention test, both in the open and the closed forced-choice question. An instrumental view about genes was considered by a significant proportion of the students in the answers to the open question in the posttest, and despite the frequency dropped in the retention test, it still reached 16 % of the answers. An example of the instrumental view and the process molecular gene concept can be found in the following students' answer:

> The gene concept is relative and depends on the way the gene will be studied. It can be understood as a physical structure that originates RNAs and proteins or as the fruit of a process or the very process, for instance (Student 1, Class B, post-test).

There were also limits, however, regarding the planned learning goals. The most important concerns the fact that, even though the commitment to the classical molecular concept significantly decreased among the students in the posttest, this was just a transitory effect. Almost the same frequency of students' answers to the open question related to this concept was found in the pretest and retention test. If we consider alternative (b) in the closed forced-choice question, we see a similar pattern, with a slight increase in the posttest that is maintained in the retention test. The following answer is a straightforward example of a student's rendering of the classical molecular gene concept:

> Gene is a nucleotide sequence that determines the synthesis of a protein (Student 5, Class B, post-test).

The return of the classical molecular concept in the retention test is not surprising. It just reveals that 5 h of lessons are not enough to challenge a view so deep rooted in the students' views, as a consequence of its reinforcement during years of schooling (as indicated by our results for high school biology textbooks). This is one example of students' prior conceptions that are resistant to change even when specifically targeted in teaching interventions. Interestingly enough, this is a prior conception that is itself a product of previous schooling. In order to reach a successful change in students' commitment to the classical molecular concept, it would be necessary to defy it repeatedly in the intervention, in several different contexts, going far beyond what was possible in the short time range of the intervention.

There was considerable overlapping of ideas related to different gene concepts in the students' answers in all the moments in which the data gathering tool was applied. In class A, 36.4 % of the answers in the pre- and posttest showed category overlapping, with this frequency increasing to 40 % in the retention test. In class B, there were 38.5 % of answers with category overlapping in the pre- and posttest, with an increase to 53.8 % in the retention test. Thus, neither the usual course nor the teaching sequence seemed to be successful in demarcating different gene concepts. This interpretation is reinforced by the analysis of the data for the free-choice closed question, shown in Fig. 16.11. Just as we saw in the study on students' views about genes, when they were free to choose several views about genes, they marked a lot of alternatives. As remarked above, conceptual variation regarding genes as represented in textbooks seems to be translated into students' allegiance to several different accounts about genes and their functions. Even though these results cannot by itself lead to the conclusion that students are wrapped up by semantic confusions and ambiguities by appealing to such a variety of views about genes, if we combine them with our findings in the textbook studies, we can have reasons to worry about this potential hybridization of different ideas regarding genes and their functions.

If we now turn to the external validation of the teaching sequence, some interesting patterns can be discerned, although we need to see them with a grain of salt, given the constraint that the experimental design included only two classes. The classical molecular concept increased in frequency in the students' answers after the intervention, not only in the posttest but also in the retention test. This finding is in agreement with our previous finding that Genetics and Cell and Molecular biology courses in the same university lead to an increase in this much challenged view about genes, despite the fact that the anomalies faced by it are addressed in those very courses. Moreover, the usual approach followed in the course did not produce even the transitory decrease in students' commitment to this concept found in the teaching sequence explicitly addressing gene function models and gene concepts.

As in the case of the intervention, the informational conception dropped in frequency in the answers to the open question when the usual approach was employed in the course, corroborating the findings of the prior investigation of students' views in the same university. But in this case the closed forced-choice question showed an opposite tendency.

Finally, a significantly smaller diversity of views about genes was observed in class A when compared with class B, in the answers to both the open and the closed forced-choice question. This is not surprising since those views were explicitly discussed in the latter but not in the former class.

Some design principles underlying the construction of the teaching sequence were not tested in this study, such as the proposed pattern of classroom discursive interactions, which require for its testing a treatment of the video-recorded material that we did not perform yet. If we consider the didactic material elaborated to the course, the historically and philosophically informed approach, the treatment of models of gene function and gene concepts, and the discussion of the crisis of the classical molecular concept using molecular phenomena already addressed

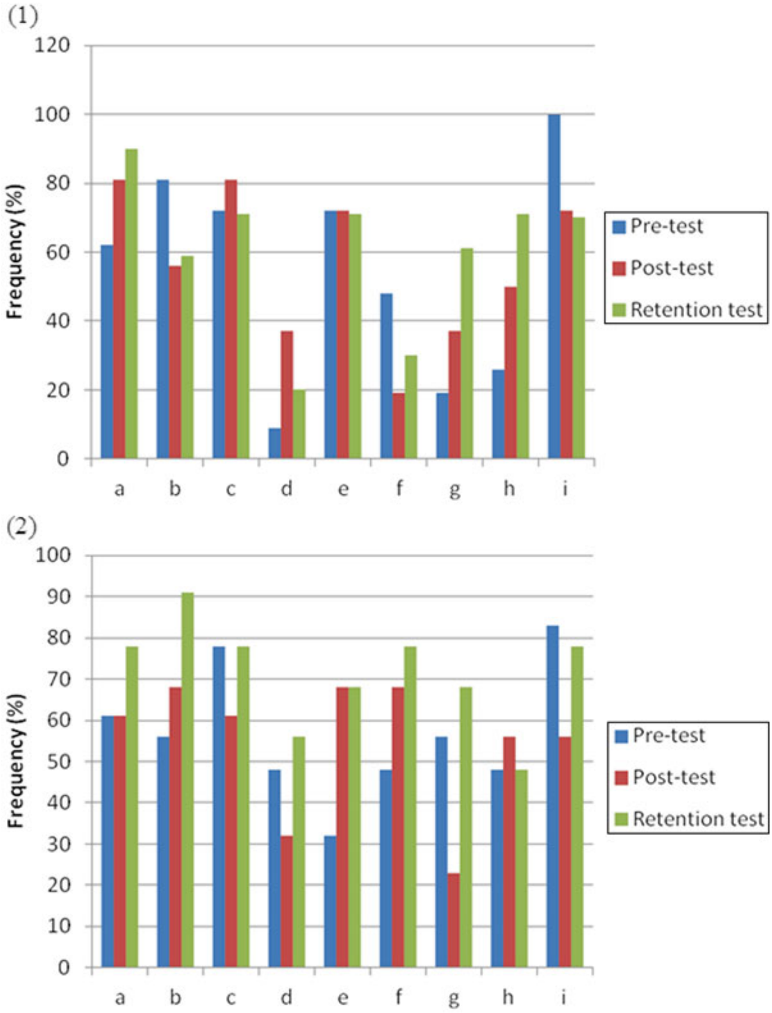

Fig. 16.11 Distribution of answers given by the students of the classes investigated to a free-choice closed question presenting several alternatives concerning the nature of genes: (**a**) Mendelian; (**b**), (**g**), and (**h**) classical molecular; (**c**) and (**i**) informational; (**d**) gene-P; (**e**) gene-D; (**f**) process molecular gene. (1) Class A (usual approach to the course, with no explicit discussion on gene function models and gene concepts); (2) class B (where the teaching sequence was implemented)

in the course, the results showed both contributions and limitations. The failures of the intervention are particularly interesting at this step of our research, since they indicated the need to introduce changes in the teaching sequence: for instance, a stronger challenge to the classical molecular concept and a more efficient discussion of the nature of models in connection with the historical construction of our understanding about genes, in order to decrease the hybridization of ideas related to different models and concepts by the students. Nevertheless, the detected advances show that it is promising to continue the investigation with a revised prototype of the teaching sequence.

16.5 Conclusion

We have been engaged in the last 7 years in a research program on the treatment of conceptual variation regarding genes and their function in school science. Following the approach to research on science education used in our lab, we took as a starting point a number of descriptive studies aiming at diagnosing views about genes found in textbooks and students and moved to intervention studies, investigating a teaching strategy for improving higher education students' understanding of scientific models and conceptual variation around genes and their function. This teaching strategy is aligned with a contextual approach to science education, using a historically and philosophically informed approach to teach not only with but also about gene function models.

Our investigations on textbooks showed the prevalence of the molecular-informational model and a significant degree of hybridization between features from different models, even when they are incommensurable. This was found in both higher education Cell and Molecular biology textbooks and high school biology textbooks. Moreover, even when the empirical findings challenging the molecular-informational model of gene function are discussed by the textbooks, conceptual lessons are not often derived from them. In high school biology textbooks, another worrisome finding was that gene-P was often used and, more than that, was often conflated with the molecular-informational model. To treat genes as determining phenotypic traits is a conceptual tool for abstracting away the complexity of the genotype-phenotype relationship in tasks like pedigree analysis, often found in high school textbooks. However, genes are most often regarded by these textbooks as codifiers of the primary structure of polypeptides or RNAs (in accordance with the classical molecular concept) and determinants of phenotypes (in line with gene-P), showing how these textbooks consistently hybridize these two gene concepts. The conflation with a molecular account of the gene transposes the deterministic assumption to DNA sequences that only determines the phenotype at its lowest level, namely, the primary structure of proteins (sometimes, also their three-dimensional structure) and the structure of RNAs. It is lost from sight, thus the complexity of development, which mediates between genotype and phenotype and involves epigenetic and environmental factors as resources in causal parity with genes (Arthur 2011; Griffiths and Knight 1998).

This provides an example of a conflation of gene concepts leading to serious consequences in genetics teaching. As gene-P, an instrumental concept depicting genes as determining phenotypes, is conflated with a realist understanding of genes as molecular units in the genome, genetic deterministic views are very likely to develop: the molecular units become determiners of phenotypes and not entities contributing to development in complex causal pathways involving other developmental resources. Preformationism lingers, then, in this manner of speaking about genes, as if traits themselves were somehow coded in the genome, and not constructed by complex developmental processes. As statements about genes-P are framed in an "updated" language, which connects it with molecular views about genes, and a historical and philosophical treatment of models is largely absent, students and teachers have no chance of understanding the instrumental nature of that concept and the explanatory context in which its usefulness is observed. The conflation between features of different gene function models not only leads to consequential problems in students' understanding of genes and their role in living beings – such as the commitment to a hyperbolic, overextended view of what DNA and genes do in cell systems – but also has implications to popular discourses about genes (or, in Keller's [2000] words, "gene talk") found in the media and even in textbooks themselves.[21]

As learning about genes becomes deeply contaminated by genetic deterministic views, students are less likely to develop a critical appraisal of socioscientific issues (Sadler 2011) related to genetics or to become capable of socially responsible decision making (Santos and Mortimer 2001) in situations involving knowledge about genes and their functions in living systems. After all, as Nelkin and Lindee (1995, p. 197) discuss,

> the findings of scientific genetics – about human behavior, disease, personality and intelligence – have become a popular resource precisely because they conform to and complement existing cultural beliefs about identity, family, gender and race […] the desire for prediction, the need for social boundaries, and the hope for control of the human future […] Whether or not such claims are sustained in fact may be irrelevant; their public appeal and popular appropriation reflect their social, not their scientific power.

Genetics is connected with socioscientific issues of central importance, such as cloning, stem cell research, genetically modified organisms, genetic engineering, use of genetic tests in society, human genetic improvement (eugenics), and reprogenetics. Sadler and Zeidler (2005) found that students' reasoning patterns in genetic engineering socioscientific issues are influenced by their knowledge of genetics, showing the importance that they properly learn about genes for their future life, not only as students but also as citizens that need to be informed by a consistent scientific understanding of the subject in order to actively and fully participate in democratic decision making.

The way these high school and higher education textbooks deal with conceptual variation can be regarded, thus, as a key problem in genetics teaching. For instance, all the historical models identified by Gericke and Hagberg (2007) were found in the high school textbooks and hybridization of features from different models was very frequent, showing how much conceptual variation was embedded in the treatment of genes, despite the prevalence of the molecular-informational model.

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[21] See, for example, Condit et al. (1998, 2001), Carver et al. (2008), Keller (2000), and Nelkin and Lindee (1995).

As observed in Swedish high school textbooks and also in textbooks from four English-speaking countries, such conceptual variation is present in the explanations about genes with no clear demarcation between multiple historical models and their domains of application (Gericke et al. in press). Features related to different models are integrated in a single, linear narrative about genes, in such a manner that no conceptual variation seems to exist.

In a study of students' views about genes in two Brazilian universities (Federal University of Paraná and Federal University of Bahia), we compared biology students who had attended Genetics courses and those who did not and found that these courses increased their commitment to the classical molecular concept while decreasing their appeal to the informational conception. Again, no connection seemed to be properly made between the treatment of molecular phenomena that put into question the classical molecular gene and their conceptual implications. Students had difficulties in dealing with conceptual variation about genes, often hybridizing features from different models, even when they were incommensurable. Moreover, the degree of such hybridization was largely unaffected by Genetics courses, probably as an effect of the textbooks used, which included those analyzed here.

The convergence between our results concerning textbooks at two educational levels and higher education students' views is indicative of the reinforcement of the students' commitment to the molecular-informational model by the textbooks, as well as of the tendency to conflate features from different historical models. As we did not analyze pedagogical practice in the Genetics course of either of the universities, we cannot show data about how that practice was influenced by the textbooks used. However, our own acquaintance with these courses allows us to say that pedagogical work is significantly framed by the textbooks, making it likely the reinforcement hypothesis proposed above. Needless to say, it will be necessary to investigate classroom work in these courses to advance a more reliable conclusion to this effect.

A significant part of the problem with the treatment of conceptual variation about genes in higher education and high school textbooks results from the lack of a historically and philosophically approach to science education. In the absence of a clear discussion of models and either their role in science or their relation with reality, teachers and students are encouraged to address genes in a naïve realist manner and, also, to conflate features of different concepts as models as if they could be simply added as descriptive hallmarks of a reality being simply presented (rather than represented) in scientific theories and models. When using these textbooks, teachers and students do not have much chance of understanding the distinct origins, domains of application, and meanings of gene concepts and gene function models. Meanings ascribed to gene are simply accumulated as genes are discussed from different perspectives chapter after chapter, with the textbooks offering on the whole a thorough mixture of ideas originating from different models, often incommensurable with one another. The gene function models offer a particularly striking example of how the use of multiple models in science teaching can generate learning problems if not taught explicitly (Chinn and Samarapungavan 2008).

It seems necessary, thus, to change the treatment of genes in both textbooks and courses towards a more contextual approach, in which students must learn not only with gene function models but also about such models. If we do so, we can also address important NOS contents in connection with the history of the gene concept. After all, the transition from the understanding of genes in classical genetics to the molecular gene with the advent of molecular biology, as well as the crisis of the gene concept and the various approaches proposed to overcome it, compose a very interesting case of conceptual change and, also, provide a window into how theoretical entities are investigated and represented in science. This does not mean that one has to deal with complex historical, philosophical, or sociological issues when writing about genes in textbooks or teaching about genes in the classroom. We take the more modest position of proposing that one needs to write and teach about gene function models in a more explicit manner, paying attention to some basic aspects, such as the nature of models and their complex relation with reality, or the variation between gene function models and gene concepts in different subfields of biology.

To argue against the indiscriminate conflation of features related to different historical models of gene function does not imply that one should defend some single and all-encompassing gene concept or model of gene function. No such single model or concept could ever capture the diversity of meanings and epistemic roles associated with genes since the beginnings of the twentieth century. The idea is rather of a coexistence of a diversity of gene concepts and gene function models in school science, but with well-delimited domains of application (Burian 2004; El-Hani 2007). It is very important to provide students with a structured, organized view about the variety of meanings ascribed to genes and their functions, in order to avoid semantic confusions and indiscriminate mixtures of meanings related to different scientific contexts. To deal with conceptual variation, it is not enough to just say that “it may not be important to know what the precise meaning of ‘gene’ is” (Knight 2007, p. 300). To entertain the importance of a clear treatment of different gene concepts and gene function models, we need just to rephrase this statement by considering a plurality of ways of understanding genes: even though it is not really important to provide a single precise meaning of “gene,” we need, still, to provide a clear and precise understanding of the several different meanings of “gene,” since they cannot be all put to each and every use. Conceptual variation is not in itself the problem, but the absence of a proper historical and philosophical treatment of models about genes and their functions, which favors the extensive hybridization of ideas related to different models.

The lack of a historical and philosophical treatment of genes is also partly the explanation for the intriguing finding that neither textbooks nor students derive conceptual lessons from the challenges to the molecular-informational model that gave rise to the so-called crisis of the gene concept. Certainly, the textbooks could derive such lessons if they were more conceptually and theoretically oriented, even if they did not give much attention to history or philosophy of science. But this orientation is also typically lacking in these textbooks.

If a contextual approach to teaching about genes, with due attention to teaching with and about models, was in place, students and teachers would have a greater chance of building an understanding of genes and their roles in living systems that could be richer and more aligned with what we currently know about the complex dynamics and architecture of the genome or the dependence of gene function on the cellular and supracellular context. This complexity is usually abstracted away in school science in favor of deterministic views, emphasizing one-to-one relationships between genes, functional proteins, and phenotypes, despite the overwhelming evidence that these relationships do not hold in most of the cases.[22] Textbook discourse should come closer to the knowledge structure of the academic disciplines of genetics and molecular biology in this case (Gericke et al. in press). It is not that high school textbooks should be necessarily updated with the last words in scientific knowledge. Since at high school students have to learn the basics of scientific disciplines, it may be more important to teach about developments of the past, which established the grounds of a way of thinking in a scientific domain, than to pursue an updated curriculum for its own sake. We need to introduce recent developments of science in school when they make an important difference for the way the students think about a domain of phenomena. This is, in our view, precisely the case with the developments of genetics and molecular biology in the last two decades. More attention should be given in genetics teaching to the current situation of the classical molecular concept, instead of just presenting it as if it was as accepted and coherent as it was in the past. At least, the fact that there are serious debates about what is a gene in the scientific community deserves attention in genetics teaching, even at the high school level. Our data do not show, however, the gene concept being treated as a controversial subject matter in either high school or higher education.

We need to investigate ways of introducing into school science the current understanding of the anomalies challenging the classical molecular concept and at least some of the alternatives to this way of understanding genes (Meyer et al. 2013). In the case of high school biological education, we think it is possible to create conditions for the students to understand that, even though the classical molecular concept has been quite important in the history of biology, it has ended up showing consequential limitations. Moreover, the concepts of gene-P and gene-D, the necessity of demarcating between them, and a critique of genetic determinism would be important additions to the high school genetics curriculum. If school science took into consideration the complex mapping between genotype, development, and phenotype (Arthur 2011), this might make a difference to students' thinking, creating conditions for the development of more informed and critical attitudes towards the deterministic talk about genes that pervades several spheres of society.

It was evident to us, then, that we needed to build and investigate an educational intervention based on a number of educated guesses about how to deal with conceptual variation about genes, which could be used as design principles for teaching interventions and, then, empirically tested in the classroom. One of the key design principles is to give a central role to a historical and philosophical approach to gene. We built such a teaching sequence in collaboration with a higher education Cell and

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[22] See, for example, El-Hani (2007), El-Hani et al. (2009), Fogle (1990), Keller (2000), Moss (2003), and Scherrer and Jost (2007a, b).

Molecular biology teacher at a Brazilian University (Federal University of Bahia) and investigated it in accordance with design-based research. The teaching sequence was oriented towards a contextual approach, explicitly addressing the historical and philosophical dimensions of science, with a particular focus on the historical construction and nature of models of gene function and gene concepts. The internal validation of the teaching sequence showed some positive learning outcomes, but also some limits in attaining the planned learning outcomes. In particular, we managed to obtain just a transitory decrease of the classical molecular concept, an outcome that was not really surprising given the fact that – as our results in the diagnostic studies showed – this view has been reinforced throughout the lives of the students at school. Moreover, we did not reach success regarding the demarcation between gene concepts and gene function models, with the same high levels of hybridization observed in the diagnostic studies being also found in the intervention studies. Even though the external validation of the teaching sequence was constrained by the number of classes available for the study, the comparison between the usual way of teaching about genes in the course and the new intervention gave some hints of positive changes: the usual approach did not lead even to a transitory decrease of the classical molecular concept, and the students' views on genes have been enriched by the teaching sequence. The first result seems robust, since it is in strict accordance with the findings of our study on students' views about genes in the same university. The second finding amounts to the major difference brought about by the teaching sequence. Nevertheless, this outcome should be accompanied by a proper understanding of models and their demarcation, in order to lead to genuine gains for the students. But this was not observed in this first prototype of the teaching sequence.

These findings gave us clear clues about changes in the intervention for its second prototyping: the classical molecular concept needs to be challenged in a stronger way, and the discussion about models, their historical construction, and the necessity of their demarcation should be reformulated in order to reach a higher level of efficacy. Needless to say, the greatest challenge will be to accommodate these changes in the limited time available for the intervention, as a consequence of the overstuffed curricula of Genetics and Molecular biology courses at the university level.

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Appendix 1: List of Analyzed Higher Education Textbooks

Alberts, B., Johnson, A., Lewis, J., Raff, M., Roberts, K. & Walter, P. (2002). *Molecular biology of the cell* (4th Ed). New York, NY: Garland.

Karp, G. (2004). *Cell and molecular biology: Concepts and experiments* (4th Ed). New York, NY: John Wiley and Sons.

Lodish, H., Kaiser, C. A., Berk, A., Krieger, M., Matsudaira, P. & Scott, M. P. (2003). *Molecular cell biology* (5th Ed). New York, NY: W. H Freeman.

Appendix 2: List of Analyzed High School Textbooks

T1 – Amabis, J. M. & Martho, G. R. (2005). *Biologia*. São Paulo: Moderna.
T2 – Borba, A. A. & Cançado, O. F. L. (2005). *Biologia*. Curitiba: Positivo.
T3 – Borba, A. A., Crozetta, M. A. S. & Lago, S. R. (2005). *Biologia*. São Paulo: IBEP.
T4 – Boschilia, C. (2005). *Biologia sem segredos*. São Paulo: RIDEEL.
T5 – Carvalho, W. (2005). *Biologia em foco*. São Paulo: FTD.
T6 – Cheida, L. E. (2005). *Biologia integrada*. São Paulo: FTD.
T7 – Coimbra, M. A. C., Rubio, P. C., Corazzini, R., Rodrigues, R. N. C. & Waldhelm, M. C. V. (2005). *Biologia – Projeto escola e cidadania para todos*. São Paulo: Editora do Brasil.
T8 – Faucz, F. R. & Quintilham, C. T. (2005). *Biologia: Caminho da vida*. Curitiba: Base.
T9 – Favaretto, J. A. & Mercadante, C. (2005). *Biologia*. São Paulo: Moderna.
T10 – Frota-Pessoa, O. (2005). *Biologia*. São Paulo: Scipione.
T11 – Gainotti, A. & Modelli, A. (2005). *Biologia*. São Paulo: Scipione.
T12 – Laurence, J. (2005). *Biologia*. São Paulo: Nova Geração.
T13 – Linhares, S. & Gewandsznajder, F. (2005). *Biologia*. São Paulo: Ática.
T14 – Lopes, S. & Rosso, S. (2005). *Biologia*. São Paulo: Saraiva.
T15 – Machado, S. W. S. (2005). *Biologia*. São Paulo: Scipione.
T16 – Morandini, C. & Bellinello, L. C. (2005). *Biologia*. São Paulo: Atual.
T17 – Paulino, W. R. (2005). *Biologia*. São Paulo: Ática.
T18 – Silva-Júnior, C. & Sasson, S. (2005). *Biologia*. São Paulo: Saraiva.

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Benzer, S. (1957). The elementary units of heredity. In W. McElroy and B. Glass (Eds.), *The chemical basis of heredity* (pp. 70–93). Baltimore, MD: John Hopkins Press.

Black, D. L. (2003). Mechanisms of alternative pre-messenger RNA splicing. *Annual Review of Biochemistry*, 72, 291–336.

Black, M. (1962). *Models and metaphors: Studies in language and philosophy*. Ithaca, NY: Cornell University Press.

Brown, A. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences*, 2, 141–178.

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Part IV
Pedagogical Studies: Ecology

Chapter 17
Contextualising the Teaching and Learning of Ecology: Historical and Philosophical Considerations

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17.1 Introduction

Ecology has gradually gained salience during the last few decades and ecological issues, including land use changes, global warming, biodiversity loss, food shortage, and so forth, seem to be gaining public attention. Though philosophers of science had given little attention to ecology, there is a lot of interesting work being currently pursued in philosophy of ecology and environmental philosophy. As Colyvan and colleagues put it, “ecology is an important and fascinating branch of biology, with distinctive philosophical issues” (Colyvan et al. 2009, p. 21). Given its conceptual and methodological familiarity with the social sciences, ecology occupies a unique position among other disciplines (Cooper 2003).

For example, ecosystem historicity, stability, complexity and uncertainty (Mikkelson 1999; Price and Billick 2010; Sterelny 2006); the role of natural history in ecological explanations (see Keller and Golley 2000 and references therein); the relationship between explanation, understanding and prediction (Peters 1991; Wilson 2009); the standard model of hypothesis testing (Colyvan et al. 2009); the role of mathematical models (Justus 2006; Odenbaugh 2005; Weisberg 2006a); and biodiversity conservation and a number of ethical or practical questions related to conservation (Odenbaugh 2007; Oksanen and Pietarinen 2004; Sarkar 2005) are all

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topics of intense discussion between philosophers, historians and practicing ecologists. And as many philosophers suggest, the process of scientific inquiry in ecology may differ fundamentally from the dominant paradigms that have been drawn from the physical sciences (e.g. Cooper 2003).

More to the point, the fact that ecology addresses complex socioscientific issues at the intersection between science and the broader social context in which the products and processes of science are situated has also resulted to burgeoning popular myths coming from society, science and even history and philosophy of science (Haila and Levins 1992; Hovardas and Korfiatis 2011; Worster 1994).

All these considerations have profound implications for teaching and learning ecology. As early as in the late 1960s, it has been argued that the teaching of ecology is accompanied with an array of discussions and controversies about the place of this discipline in the educational system that cannot be easily compared to other disciplines (Lambert 1967).

In the next sections, we will first present an overview of shortcomings and failures in ecology education. Then, we will attempt to show that a comprehensive philosophical understanding of ecology might prove invaluable for battling misconceptions and achieving ecological literacy. We review some of these philosophical and historical considerations in ecology and explore a number of cases where the implications of these discussions might make a difference to ecology education. The potential to overcome unfruitful or superficial descriptions that have long plagued ecology and hindered understanding is a major incentive in this direction. Thus, we focus on two interrelated issues:

(a) The role of natural history research in ecology and its relationship to the standard hypothesis-testing model
(b) The role and understanding of ecological models in the ecology classroom

Our choice does not only attest to the fact that these two topics are being heavily discussed but also to their close relation to both educational practice and major misconceptions concerning scientific inquiry in ecology. Finally, we suggest ways in which a historically and philosophically informed curriculum might be developed to account for ecology's distinct nature.

17.1.1 Shortcomings and Failures in Ecology Education

Ecology is considered a young science. The same may be said for ecology education. Ecology started to seriously be part of education in European and North American countries during the 1960s (Berkowitz et al. 2005; Hale and Hardie 1993). Today most people would agree that ecology is an integral part of a contemporary science education curriculum (McComas 2002a). A general consensus seems also to exist among educators regarding both the necessity of educating ecologically literate people and the meaning of ecological literacy itself. More specifically, it is agreed that ecology is the science of interactions and multiple causal factors (Taylor 2005).

It is about patterns of population growth, dynamics of intraspecific and interspecific relationships, structure and function of ecological systems and flow of energy and matter through ecosystems. Therefore, as Berkowitz and colleagues (2005) argued, understanding the nature of causal factors, constraints and feedbacks in ecological systems, defining the key components of a system and its connections and understanding structure/function relationships and the kind and function of ecological processes in space and time are crucial for an ecologically literate person. Moreover, ecology educators assume the responsibility for ensuring that students gain the intellectual tools to engage fully in environmental debates and decision making. In this context, ecological literacy presupposes a deep and full understanding of ecological concepts and reasoning, while also considering the nature of ecological science and its interrelationship with society (Berkowitz et al. 2005).

Research on ecology teaching and learning, however, has consistently identified a considerable lack of understanding of core ecological concepts and processes in all educational settings regardless of age and/or background (Stamp et al. 2006). A first main cause of the failure of ecological education to accomplish its goals could be attributed to disagreements on what ecology is and what and how it should be taught in classrooms. A large part of 'ecological' content in science textbooks is in fact about taxonomy, morphology or physiology, rather than ecology per se. The science of ecology, i.e. the study of the relationships of living organisms between each other and their nonliving environment, covers a rather small part of most national science education curricula (McComas 2003; Tunnicliffe and Ueckert 2007). In most cases, ecology education could be characterised as a teaching of 'ecological bites' rather than a comprehensive and thorough understanding of ecological systems, structure and function (Korfiatis and Tunnicliffe 2012). For example, Bravo-Tortilla and Jimenez-Aleixandre (2012) noted that energy transfer would usually be taught in only one session in Spanish high schools. They also commented that Spanish educational authorities seem to be totally unaware of the time that would be needed in order for the students to be able to adequately situate the concept in different contexts and understand its centrality for sustainable resource management.

At the same time, complaints about the insufficiency of educational material to foster ecological literacy objectives are rather abundant and they do not seem to be taken into account for reforming curricula. About 20 years ago, Hale (1991) and Hale and Hardie (1993) argued that the English Science National Curriculum falls far short of providing an adequate and balanced approach to ecology, as a number of key concepts are omitted. About a decade later, Slingsby and Barker (2005) lamented that in several cases the ecological content in the English curriculum was out of date, based on a 1950s perception of ecology, or relied heavily on social policies that could be easily misconstrued as ecological concepts. Similar complaints about the inadequacy and outdatedness of the ecological content in textbooks can be found in other regional curriculum studies like Berkowitz and colleagues (2005) in the case of the USA and Korfiatis and colleagues (2004) and Lemoni and colleagues (2011) in the case of the Greek primary school curriculum.

Many writers also suggest that there might be a difficulty in handling ecological concepts such as food webs, recycling and energetics that is common for all students across age cohorts (Barker and Slingsby 1998; Demetriou et al 2009; Grotzer and Bell Basca 2003). The roots of this difficulty are to be traced in the dynamic and systemic nature of ecological processes and the thinking skills that are necessary for someone to develop in order to cope with this systemic nature. Studies by Green (1997, 2001) propose that students might reveal the beginnings of a capacity to think about interactions in natural systems but that this is frequently overwhelmed by task complexity. Since system thinking skills are necessary to follow the complexity of ecological systems (e.g. Taylor 2005; Yodzis 2000), employing linear and unidirectional processing of interactions in ecological systems will necessarily result in oversimplifying structure and dynamics in such systems and in developing profound misconceptions of the causal interactions that occur in such systems (White 2008). When tracing the effect of a change or perturbation through the structure of a complex system, students tend to follow this effect along one direction only, away from the locus of perturbation in terms of the structure of the system, and they do not seem to appreciate or predict interactions. For example, in a hypothetical situation where a population of wolves and a population of deer interact in a forest, students usually assume that wolves will first consume all deer and then die since they will have exhausted their feeding sources. Thus, they seem to forget the existence of regulatory mechanisms in many populations that do not allow them to increase indefinitely until they exhaust all resources and go extinct.

The complexities of interactive systems with multiple entities are admittedly hard to grasp, but a failure to appreciate even the possibility of interactions and feedback loops seriously compromises understanding of the workings of the natural environment (White 2008). The lack of understanding of complex systems function and interactions seems to be accompanied by rather teleological explanations, which are quite common in naive accounts of ecology and which raise static or even essentialist representations of nature (Hovardas and Korfiatis 2011). As students find it difficult to follow the effect of a disturbance through different branches of a food web, or, more importantly, the feedback effects taking place in interactions between populations (Hogan 2000), they tend to think that any disturbance in an ecosystem will eventually result in its collapse (White 2008). Alternatively, they may hold that no matter the kind or the magnitude of the disturbance, the ecosystem will eventually recover to its initial state (Ergazaki and Ampatzidis 2012).

However, none of the dimensions of ecological thinking should be seen as completely beyond the capacities of even the youngest learner. To the contrary, young people are perfectly able to grapple with evidence, systems, space and time throughout their lives, and this might lead to substantial learning benefits provided an adequate support in the form of scaffolds is given (Slingsby and Barker 2005). The crucial problem in ecology educations is often the inadequate approach to teaching. Within the above framework, the challenge for ecology education is to develop a curriculum that flows from simple to more complicated contexts without introducing new misconceptions. Barker and Slingsby (1998) and many other scholars before them (Leach et al. 1995, 1996a, b; Webb and Boltt 1990) have highlighted the possibility that in an attempt to make ecological concepts ‘understandable’, these concepts may be integrated in the curriculum in such an oversimplified way that they become essentially ‘incorrect’. Indeed, many textbooks, while overloaded with heavy concepts, at the same time, include the core concept of trophic relationships as a formation of simple, linear food chains and not as food webs, despite the fact that the latter can be a more comprehensive approximation of trophic relations (Barker and Norris 2000).

The food-web representation offers more alternatives to elaborate on the outcome of a change in the web structure, whereas the food chain implies more drastic alterations after a change has occurred (e.g. loss of a species will dismantle the chain). In the food-chain representation, the structure can be irreversibly impacted if a species disappears, since each species occupies a unique and crucial position in the linear configuration of the food chain and cannot be readily substituted by another species. However, the removal of a species in the food-web representation does not necessarily lead to the collapse of the structure. In this case, relations between species that will remain in the food web will sustain the structure and the food web will be reorganised. For that professional ecologists have long warned for the necessity to clarify the concept that ‘everything is connected to everything’ through ecological education and not to consider it as a metaphysical principle, as many educators currently do (Berkowitz et al. 2005).

Another source of constraints for the development of proper educational approaches is the contradictory and often superficial discussion of the philosophical and theoretical base of ecology. This results in serious failures in communicating ecological science to the public and in targeting issues that, in relation to schools, might actually influence the curriculum. In textbook and public understanding of science research, significant concerns have been raised as to the extent that analogies, metaphors and symbols are invariably mixed with ecological subject matter, thus promoting an environmentalist rhetoric that is often closer to lay than scientific knowledge (Berkowitz et al. 2005; Cuddington 2001; Mappin and Johnson 2005). A characteristic example of the close interrelation between popular understandings of ecology and their classroom implications is the presumed ‘holistic’ nature of ecological science. Indeed, many scholars consider ecology as a science alternative to the western mechanistic Cartesian paradigm of modern science. Bowers (2001), for example, suggested that “ecologically oriented sciences” represent a different worldview, against the reductionistic Newtonian sciences. Adhering to this holistic orthodoxy, in many school curriculums across the world, ecology teaching is characterised by a focus at the ecosystem level, and an overemphasis on sophisticated and highly abstract concepts such as energy flow (Magnetorn and Hellden 2007), which may be introduced at inappropriate age levels. For instance, in the Greek and Cypriot curriculum, the notion of the food pyramid is introduced already in the second or third grade of the elementary school. We strongly believe, however, that this educational level cannot support a thorough comprehension of such complex concepts. In a similar vein, Ryoo and Linn (2012) contented that middle school students in the USA are grasping to deal with abstract concepts such as energy flow as they are not given the opportunity during prior instruction to build on their understanding of concrete mechanisms and processes.

Likewise, Slingsby and Barker (2005) argued that while in the English curriculum there is considerable emphasis on ecology at GCSE level (14–16 years), it is dominated by the concept of the ecosystem and a concentration on complex abstractions such as energy dynamics of food chains, the carbon and nitrogen cycles, the greenhouse effect and the consequences of global warming. As a result students are facing considerable difficulties in locating species and their role in food webs, with the most striking case being that of decomposer species (Sander et al. 2006; Demetriou et al. 2009). Another set of related and reoccurring misconceptions concerns the food pyramid concept and specifically the flow of energy and the decrease of biomass across levels. In fact, the majority of students are seldom able to comprehend and explain the shape of the food pyramid in terms of energy flow or biomass decrease. Instead, they usually believe that energy accumulates at the end of a food chain, or that total biomass reaches a climax at the end of a food pyramid, or even that ecosystems recycle energy (see, e.g. D'Avanzo 2003; Stamp et al. 2006).

17.2 Ecological Inquiry, Natural History Research and Ecological Education

The "scientific inquiry" approach—i.e. an approach that focuses on scientific processes related to collecting and analysing data and drawing conclusions—is currently the dominant form of teaching and learning proposed by most educators and educational researchers in the science education community. There is a vast amount of literature scrutinising the possible advantages and disadvantages of inquiry learning and its background philosophy from a philosophical, epistemological and educational point of view. However, a point of concern that has only recently started attracting the interest of researchers is that "scientific inquiry" in the science classroom often takes the form of simple exercises on hypothetico-deductivism, in the sense that it relies heavily on the "hypothesis–experiment–justification/rejection" rubric. As Windschitl and colleagues (2008) indicated, reference to a universal scientific method is common in discourse at all levels of science education, having, with only minor variations, the form of the following: observe, develop a question, develop a hypothesis, conduct an experiment, analyse data, state conclusions and generate new questions.

This actually seems to be the iconic representation that actively shapes how teachers and learners think about scientific practice. When used as an instructional protocol among others, this approach has allowed many teachers to develop activities that motivate young learners to ask questions, test hypotheses and work with first-hand data, but its hegemonic appearance misrepresents fundamental intellectual work done by contemporary scientific disciplines like ecology. To grasp an idea of what a better learning approach for ecology should look like, it is imperative that we turn to the science of ecology itself and outline some of the characteristics of ecological research.

17.2.1 Natural History Research and the Problem of Scientific Method in Ecology

For many years, the relationship between ecology and one of its predecessors, i.e. natural history, was a skeleton well hidden in the closet. In light of this old secret, Price and Billick (2010), in the introduction of their edited volume on the ecology of place, raised the rhetorical question "Where do ecological ideas come from?" The reply provided by Kingsland (2010) was that they do not spring deductively from the minds of ecologists, but rather from an interaction between ecologists and the place of their studies. Indeed, ecology has often been challenged as relying too much on natural history during its formative years, i.e. in the study of organisms in their environment. This kind of studies has been accused of constituting more of a merely descriptive science, without any explanatory or predictive power. Natural history was a distant relative, a kind of unsophisticated activity, restricted in collections of data that cannot be generalised. As Kingsland (2005) notes, during the discipline's formative years, ecologists had to fight to find their niche and not to be seen as a kind of scientific birdwatchers.

As ecology matures, however, it seems that ecologists are no longer afraid of the close embrace with natural history. Ecologists nowadays defend the role of natural history by claiming that prolonged study of organisms in their natural environment is the only way to understand problems in evolution, adaptation and biogeography and that "all good ecology is founded on a detailed knowledge of the natural history of the organisms" (Krebs 2010, p. 285). They also assert that natural history is not an old-fashioned activity of collecting specimens from the field, but a scientific activity, which presupposes careful design and inquiry. As Grant and Grant (2010, p. 111) put it, "…knowledge of natural history helps to frame initial questions and guides observation and it is indispensable for a comprehensive interpretation of the results" (Grant and Grant 2010, p. 111).

It became apparent that theoretical and empirical ecological research brought onto the frontline research methods that were not considered so sophisticated by the so called 'hard sciences'. In ecological research, experimentation might be as frequent as observation or even less frequent. Comparative methods are also common in ecology, as well as in sciences like evolutionary biology and geology, where historical evidence is significant. Multiple investigations and bodies of evidence of different kinds are usually brought to bear on assessing a hypothesis. Context dependency in ecological studies (Bowen and Roth 2007) precludes prescriptive field-based, replicable investigations for which the outcomes may be predetermined. Finally, though the formulation of hypotheses is indispensable for conducting scientific research, the role of hypotheses in scientific fields like ecology is not primarily to inform experimentation in terms of prediction (Shrader-Frechette and McCoy 1994; Stephens et al. 2006) but may actually serve other desiderata, such as to guide data selection and propose explanations (Marone and Galetto 2011).

So, which should be a proper scientific method for ecology? Much ink has been spilt on discussions about the science of ecology and hypothetico-deductivism during the 1980s. The major agreement that came out of the debate was that ecology is not and should not be treated as a hypothetico-deductive endeavour and that long-term ecological field research goes beyond the 'popperian exercise' of providing 'yes' or 'no' answers to specific hypotheses (Kingsland 2010). This agreement along with emphasis on fundamental differences among scientific disciplines and the questions scientists ask as well as the approaches they take when pursuing answers to those questions (Rudolph 2005) allows for similar developments in science education. The problem seems to be that educational practice has not followed developments in science and philosophy of science (Duschl et al. 2007). To this problem we now turn our attention.

17.2.2 Inquiry Approaches and Ecology Teaching

Although there is an abundance of methodological rules operative in the sciences, scientific inquiry in the science classroom and across all educational levels has tended to feature hypothetico-deductivism as a nearly universal scientific method (Windschitl et al. 2008). At the same time, the scientific inquiry approach, as often practised in classrooms, all too frequently promotes experimentation, which is based on the separation between control and experimental conditions and on a single set of observations that is considered definitive in testing an idea (i.e. the "critical experiment" as noted by Nadeau and Desautels 1984) as the only method of generating data. These features constitute a double challenge for science education more generally and ecology education in particular.

As Duschl and colleagues (2007) established, during the last 50 years or so, we have witnessed a radical change in discussions about the nature of science, which can be described as a shift in focus from science as experimentation to science as explanation, model building and revision. Causal explanations grounded in control of variable experiments have given ground to statistical/probabilistic explanations grounded in modelling experiments. Indeed, several criticisms on the use of the standard hypothesis-testing model have been quite intense in ecological and evolutionary studies during at least the last four decades.[1] As Stephens and colleagues (2006) described, major sources of fallacy are associated with an inappropriate focus on statistical significance over understanding/explanation in the case of highly complex and variable ecological systems under study, an overstatement of statistical inferences as well as on philosophical considerations related to the dichotomous choices imposed by the hypothetico-deductive model. Colyvan and colleagues offered an illustrative example of this line of arguments:

> For example, a survey may fail to demonstrate that land clearing results in a reduction in the number of bird species in the area in question… However, this failure is often an artifact of the model of hypothesis testing employed. Standard hypothesis testing is very conservative, in that it guards against false positives (type I errors). But sometimes in science, false

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[1] See, for example, Ayala (2009), Brandon (1994), Haila (1982), McIntosh (1987), Peters (1991) and Price and Billick (2010).

> negatives are more worrying. Believing that no extinctions are occurring or that land clearing is having no impact on the number of bird species, for example, can be very dangerous null hypotheses to fail to reject (Colyvan et al. 2009, p. 22).

What is important for this discussion is that alternative techniques for testing alternative hypotheses, generating new hypotheses or predictive models and assessing descriptive findings, have been incorporated into ecology including Bayesian models, effect size statistics and IT techniques (Knapp and D'Avanzo 2010; Stephens et al. 2006). The development of these methodologies attests not only to the failures, shortcomings or inappropriate use of the hypothetico-deductive model but also to the need for addressing the pluralistic nature of ecological research questions, data and goals.

Hence, educators should not rashly embed aspects of a typical inquiry learning procedure in ecology education (e.g. hypothesis testing and direct experimentation). There is a need to promote a different conceptualisation and operationalisation of inquiry in ecology education, which should reveal the necessity of a variety of methods for data generation and interpretation to develop solid understandings, explanations and predictions of ecological phenomena.

17.2.3 Implications for Teaching Ecology

From an educational point of view, all these arguments bring new emphasis on longitudinal outdoor settings, i.e. the study of organisms into their environment, and raise the importance of educational activities such as observations and comparison, rather than direct experimentation.

Although in most cases observation is the starting point for science, there are few studies of science education literature that have focused on a comprehensive account of observation (Tomkins and Tunnicliffe 2001), which involves skills such as description of phenomena, looking for patterns and making measurements. Eberbach and Crowley (2009) suggested that educators and experts had underestimated the complexity of observational practice, its interrelationship with disciplinary knowledge and the degree to which teachers and students needed scaffolding to support scientific observation. They state that experts build hierarchical, highly organised structures (within their discipline) that enable them to effectively encode and organise the observable world differently from novices and to efficiently notice and recall meaningful patterns. Moreover, systematic observation and comparison can be, for an expert, a powerful method for supporting complex hypothesis testing without experimental manipulation. Novice's observational skills, on the contrary, are portrayed as unsystematic, unfocused and unsustained. In a scientific context, novices might be described as classic "dust-bowl empiricists" who make lots of observations but have trouble encoding evidence, making valid inferences and connecting observation to theory. Accordingly, children's everyday observations have been shown to do little work towards building complex scientific understanding of natural phenomena (Ford 2005). When children are cast into an activity with inadequate knowledge and instructional support, observation becomes a weak method for collecting data rather than a powerful method for scientific reasoning. Indeed, as Tomkins and Tunniclife admitted:

> …traditionally it was very fashionable to make the meticulous observing and drawing of biological specimens an objective in itself, but this did not necessarily lead to creative thinking about either the organism or indeed its biology. (Tomkins and Tunnicliffe 2001, p. 793)

Thus, Eberbach and Crowley (2009) argued that learning to observe scientifically necessitates bootstrapping between specific disciplinary knowledge, theory and practice.

Therefore, ecological education in the field should not be seen as a pleasant outdoor recreational activity, but as a structured process that forms the basis for new theoretical and empirical ventures. Guided science experiences outside the formal classroom require children to think critically and to value their own experiences and ideas. When being properly scaffolded, children can proceed from the experience of observational data to an expression of meaningful interpretation, such as the integration of data and inference or the making of new hypotheses (Tunnicliffe and Ueckert 2011). Likewise, Feinsinger and colleagues (1997) proposed that the first steps towards ecological literacy are for inquirers to become familiar with the natural history of their local and abiotic environments and from this to progress to the acquisition of skills of posing interesting questions about their own surroundings and to the consideration of the consequences of various human activities. Only in such a context could an understanding of ecological concepts and content be meaningfully acquired.

This orientation can be best served by a lesson sequence approach in contrast to the dominant single-lesson approach (Duschl and Grandy 2008). In an ecology education context, ‘observation’ is not just ‘looking at things’ but has to involve describing features of ecological phenomena, looking for patterns, developing and testing models and proceeding to making measurements. These processes require moving between conceptual and observational modes, which may not be served by the traditional approach to experimentation.

Demetriou and colleagues (2009) proposed a curriculum for comprehending trophic relations in elementary school, which is based on guidelines for the identification of organisms, their food preferences and the construction of a food web using real data. Students first discuss and elaborate on a rubric (classification key) depicting signs of organisms, namely, specific traces that are an indication of the presence of specific organisms. Anytime students discover a sign (e.g. a leaf bitten by a worm), they can be quite sure that this sign indicates the presence of an organism. A point to highlight here is the fact that many researchers can gather a big amount of evidence concerning the behaviour and habits of an organism only by following its signs. After having discussed the rubric, students go outdoors to select evidence on the presence and behaviour of organisms. They then proceed to a reconstruction of a food web by combining presence/absence data they have selected and feeding habits of organisms that are expected to be found in the study area. The food web can be used as a tool for following changes in the structure and dynamics of the biocommunity under study under a range of possible scenarios (e.g. change of food sources according to shifts due to seasonality). Students can pose questions and use the reconstructed food web as a guide to prepare their answers and support their reasoning. A pilot study of this educational approach revealed that fourth graders are able to construct quite precise and complicate webs, including a large number of species and drawing multiple trophic connections (Demetriou et al. 2009). Without wishing to downplay the need of providing crucial details on the functional and behavioural characteristics of food webs, the educational intervention proposed here could serve as an introductory basis for studying food webs.

This is clearly an investigation where participants are moving between conceptual and observational modes, but these actions cannot be called experiments in the traditional sense. Moreover, the artefacts of the learning activity, and more specifically the food-web diagrams, can serve as a basis for the development of additional ideas and models. Students can move on to test these ideas by developing explanations and creating arguments in support of their models. Consequently, models and modelling activities are emerging as an important aspect of both ecological scientific practice and ecology education. Indeed, it is more than often suggested that ecology education should provide more opportunities that lead to model-based inquiry and support the dialectical processes between data, measurement and evidence on the one hand and observation, explanation and theory on the other. It is at the study of that aspect of ecological inquiry that we will turn our attention now.

17.3 Ecological Models in the Science Classroom

Physical, scale, analogue, mental, theoretical, historical and mathematical models as well as other kinds of representations have triggered animated debates between philosophers and historians of science. Since the early 1960s, extensive accounts of models as the basic constitutive parts of theories or as mediators between theoretical structures and the world can be found in their writings.[2] These discussions are collectively known as the semantic or model-based view of science, though forming a rather heterogeneous group of ideas about the nature of models, they all attest to the importance of the concept and understand theories as sets of models. In talking about the structure of theories, all proponents of the semantic view roughly agree that their analysis is applicable to all scientific theories, while most of them, at least in the early days, understood models in a formal analysis context.

17.3.1 Models and Modelling in Science Education

Despite emerging criticism, the model-based view has attracted the interest of psychologists and science educators.[3] Model construction and deployment are seen as activities that extend well beyond scientific practice to include all sorts of human

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[2] For a comprehensive review of the semantic view literature, see Godfrey-Smith (2006).

[3] Various interesting perspectives focus on theory construction per se and distinguish between modelling and other kinds of theoretical practices (e.g. see Weisberg and Reisman's (2008)

endeavours (see, e.g. Giere 2004; Redish 1994). Especially science educators, more than often, emphasise the need to incorporate models and modelling in school curricula, while advocating for a general modelling approach in education (e.g. Chamizo 2011; Koponen 2007; Portides 2007). Indeed, a number of researchers have established that modelling enhances students' problem-solving abilities, supports content learning and advances the understanding of the characteristics of science and scientific practice (e.g. Wynne et al. 2001; Schwarz and White 2005). As Gilbert and Treagust (1993) noted, models are at the same time fundamental components of scientific method and products of science, while also serving as major learning and teaching tools. The appreciation of the role of models has also led to a series of studies, which offer either profound historical and philosophical accounts of important scientific models (e.g. see McComas 2002b; Matthews 2005) or empirical results in support of this didactic orientation (Flores-Camacho et al. 2007; Prins et al. 2009; Silva 2007).

Despite this broad agreement, the terms model and modelling are used rather ambiguously in science education.[4] Thus, models are often described as simplified representations used to predict or explain phenomena (Schwarz et al. 2009); data fitting and evaluation devices (Chinn and Brewer 2001); a method to inform the development of ideas, make predictions and explore alternative explanations (White 1993); a device for describing, explaining and predicting phenomena as well as communicating scientific ideas (Oh and Oh 2011); and so on. This vagueness on what conceptions of models and modelling we put into practice seems to be a major difficulty when designing and executing inquiry-based activities and may well be responsible for both students' and teachers' inadequate and/or limited content knowledge (Grosslight et al. 1991; Harrison and Treagust 2000; Van Driel and Verloop 1999). All in all, traditional curricula seem to neglect models' tentative nature and present them as mere—i.e. non-mediated but reduced, static or simplified—copies of the real thing being studied (Prins et al. 2009).

Things become even worse when mathematical models come into play as students are unable to interpret the symbolic language used and produce qualitative explanations (De Lozano and Cardenas 2002; Korfiatis et al. 1999; Silva 2007). As a case in point, the vast majority of undergraduate biology students find themselves struggling with ecological models like the notorious Lotka–Volterra equations in every introductory population ecology course around the world. Indeed, the relatively simple mathematical model that Alfred Lotka (1925) and Vito Volterra (1926) separately introduced to describe the population cycles of a predator–prey system has been eloquently accused of inducing terror, hence the expression *Lotka–Volterrorism*, among students (Boucher 1998). In sum, despite the vigorous discussion and research in the area, both students and teachers seem to still fail to appreciate

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discussion on the difference between modelling and abstract direct representation and Godfrey-Smith's (2006) critique of the semantic view's formalism).

[4] This is not to say that philosophers of science are in a better shape; as Godfrey-Smith (2006) wrote, 'The term 'model' is surely one of the most contested in all of philosophy of science' (Godfrey-Smith 2006, p.725).

the importance of modelling in scientific practice since they are merely introduced into questions like 'what is a model?', 'how do we model?', and most importantly 'why do we model?'.

Following scholars like Schwarz and colleagues (2009) and Adúriz-Bravo and Izquierdo-Aymerich (2005), we are confident that bringing these questions into classroom discussions will enable students and teachers to develop a broader understanding of scientific methods and plan innovative educational interventions. Like Passmore and colleagues (2009), we believe that inquiry-based activities should include the development, use, assessment and revision of models and related explanations. We also agree that to fully appreciate the diversity of scientific practice, these activities should be explicitly grounded in a specific context and always address epistemic reasoning in relation to emerging scientific problems.

To this end, we suggest that the philosophical discussion about models in ecology presents a great opportunity to focus on actual scientific practice. Being necessarily idealised in comparison to the real-world systems they represent, ecological models are diverse and fulfil different desiderata. Next, we will briefly touch on some of these issues and highlight why a pragmatic and pluralistic turn might prove more fruitful for classroom explorations than more generic accounts.

17.3.2 Models and Modelling from a Philosophy of Ecology Perspective

When models are discussed in philosophy of ecology or biology, Richard Levins' seminal contributions come first to mind.[5] In his most cited works, 'The Strategy of Model Building in Population Biology' (1966) and 'Evolution in Changing Environments' (1968), as well as in a number of subsequent writings,[6] Levins offers enormous insight on recurrent philosophical and practical questions about models and modelling. His concerns grew out of the need to deal with the extreme complexity of biological systems as well as from a great dissatisfaction with the prevailing empiricist, reductionist and overspecialised philosophy of American science.

Levins' ideas have been immensely influential among biologists and his discussions of modelling still appear even in introductory textbooks. Philosophers of science were a bit late to discover this discussion, with the exception of William Wimsatt (1981, 1987) whose major concerns were remarkably close to Levins'. Since the 1990s, however, Levins' views have been carefully scrutinised providing

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[5] Richard Levins is a well-known theoretical population biologist who has contributed significantly to our attempts to understand and influence complex systems. His work has often crossed disciplinary boundaries and actively integrates issues of history, philosophy and sociology of science. As Haila and Taylor (2001, p.98) wrote: "…in his research, concrete questions, theory and philosophy go hand in hand… (while his) pioneering role in developing ideas on ecological complexity is widely known" (Haila and Taylor 2001, p. 98).

[6] See, for example, Levins (1970, 1993, 2006).

the basis for fruitful reflections and insight.[7] Here, we will briefly develop some of the major themes emerging from his work along with recent considerations on the epistemic questions surrounding modelling. We hope that these insights will prove useful to classroom discussions. Next, we will focus on three interrelated issues: (a) modelling strategies and desiderata, (b) models and real-world systems and (c) methodological pluralism.

17.3.2.1 Modelling Strategies and Desiderata

As already mentioned, every introductory ecology (or population ecology) module introduces students to what is often called 'Levins' classification of models'. In a nutshell, what they are taught is that models can be either general or realistic or precise and therefore scientists devise or use each 'kind' of model according to their goals or even aesthetic criteria. And the question is what is wrong with this formalisation? Is it true to the philosophical discussion? Our contention is that it is both misleading—as it turns an epistemological venture to an essentialist account—and largely not useful; students barely ever need another classification.

In his 1966 paper, Levins did argue that when building models—in his case mathematical—of complex systems, scientists must inevitably trade off between different model attributes and follow alternative strategies that best match their desiderata. In short, he suggested that there cannot be a best all-purpose model, i.e. one that simultaneously maximises generality, realism and precision, while remaining manageable and helps us understand, predict or even modify nature.[8] Therefore, biologists either sacrifice generality to realism and precision (as in the case of highly predictive fisheries models), choose generality over realism and precision (as in the case of the classical Lotka–Volterra predator–prey systems) or prefer realism and generality to precision and produce qualitative results (as in the case of the equilibrium theory of biogeography). Several years later, Odenbaugh (2005) similarly suggested that models in theoretical ecology serve different purposes: (a) they are used to explore possibilities, (b) they can serve as basis to investigate more complex systems, (c) they lead to the development of conceptual frameworks, (d) they can provide predictions and (e) they can generate explanations.[9]

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[7] See, for example, Godfrey-Smith (2006), Justus (2006), Haila and Taylor (2001), Odenbaugh (2003, 2005, 2006), Orzack and Sober (1993), Palladino (1991), Taylor (2000), Weisberg (2006a, b), Winther (2006), and Wimsatt (1981, 1987).

[8] In this context (Levins 1966, 1993) one could arguably suggest that generality refers to the number of real-world systems a model applies to. Realism refers to the representational accuracy of a model, i.e. how well the structure of a model represents the structure of a target system. Finally, precision could be understood as fineness of specification.

[9] The issue of explanatory success of highly idealised models is a very interesting discussion that cannot be undertaken here. However, we briefly note that even these models may have explanatory power if our idealisations do not affect the basic causal relationships or if we see our explanations as sketches of an explanation.

What these initial ideas, along with more recent considerations, contribute is the concept of trade-offs between often-conflicting epistemic aims in light of our cognitive and even technological limitations (Odenbaugh 2003). Levins did not offer a trichotomy of models but an account of the practices of modelling in biology. Thus, one might rightly suggest that these arguments are pragmatic and historical. The notion of strategy, however, is vital. Scientists explore sets of options depending on their specific research questions and try to best exploit possibilities through a configuration of resources within a challenging environment. Both their strategies and desiderata may change given the technological capacities and the altering demands at the intersection of science and society. Limitations may as well become more flexible, but ecologists will still have to device strategies to deal with the characteristic complexity of the inherently dynamic and contradictory ecological systems.

For science educators and students, these discussions seem to be an excellent starting point to explore core issues about how scientific inquiry proceeds and about the plurality of scientific methods and scopes and the limitations of our methods and research agendas. Furthermore, they bring to the forefront issues related to the science/society interaction, especially in terms of the changing goals that society sets for science and vice versa. For example, the rise of environmental awareness has put pressure on scientists to device models that will best help preserve or even modify nature. This in turn has resulted in a proliferation of more predictive and realistic models but also in an emphasis for the need to explore alternative hypothesis and understand and explain nature before taking action. Finally, they bring to life an often-disregarded discussion about the relationship between science and technology in terms of how technology may empower and advance science and vice versa.

17.3.2.2 Models and Real-World Systems

Ecologists have consistently expressed their discomfort with the proliferation of highly idealised models that are seldom tested against real data (see, e.g. Peters 1991; Simberloff 1981; Strong 1983). In Daniel Simberloff's words:

> Ecology is awash in all manner of untested (and often untestable) models, most claiming to be heuristic, many simple elaborations of earlier un-tested models. Entire journals are devoted to such work, and are as remote from biological reality as are faith-healers. (Simberloff 1981, p. 52)

Philosophers of ecology, on the other hand, have also been arguing that explanation, prediction and correspondence with data are not the only goals for modelling, and therefore, reality is not the benchmark for all models (Cooper 2003; Odenbaugh 2003; Taylor 1989, 2000). For example, Taylor (2000) defined three possible roles for models according to their relationship to reality: (a) *schemata* highlight biological processes and when expressed mathematically become exploratory tools which produce diverging outputs and explore various aspects of the specific world generated by schemata, (b) *redescriptions* allow for the formulation of statistically testable hypothesis and low-level generalisations as long as previously observed patterns still hold and (c) a model is characterised as a *generative representation* if it does not only fit the data but its accessory conditions also seem to hold true.[10] Thus, the model is a higher-level generalisation that not only explains the phenomenon but also allows making future predictions.

This approach does in no way disregard ecologists' concerns about models being mathematically inspired exercises on pieces of paper. On the contrary, it is a call for an even closer rapprochement between theoretical and empirical research. As Odenbaugh (2005) rightfully suggested theory construction through modelling is an indispensable part of doing science, advancing our understanding and allowing for new questions to emerge. At the same time, empirical research does not only validate theoretical claims but also offers insights and new directions for theoretical endeavours.

In any case, however, models are constructed systems with patently unreal assumptions about their variables, parameters and the relationships that hold between the two. Models grow out of a process of simplification, a process of abstraction and the addition of assumptions needed to facilitate a specific study. This obviously means that all models are idealised and their idealisations are legitimate not only in relation to the reality described but also according to the state of science and the purpose of study they were designed for. In this sense, as Levins suggested back in the 1960s, "…all models leave out a lot and are in that sense false, incomplete, inadequate" (1966, p. 430).

Before we turn to our final point, we believe that this line of thinking adds several new points of concern for classroom discussions, especially in the light of the importance that students, even after explicit discussion about the multiple roles of models, seem to put on explanatory or predictive success (Svoboda and Passmore 2011). For example, students and teachers could work on some of the following ideas: (a) even more realistic models, either predictive or explanatory, are not just simplified reality; (b) simple, exploratory or conceptual models do not evolve to become predictive or explanatory since this is not the purpose they were designed for; (c) matching real-world situations, either through describing causal mechanisms or making accurate predictions, is a fundamental goal of science but not the standard all models should follow; and (d) the final test of highly idealised models should be their ability to produce new generations of models that are explanatory and/or predictive. For example, the classic highly idealised Lotka–Volterra prey–predator model, when supplemented with more detailed biological information, like adding a saturation coefficient for the predator population, produces new generations of models, which are much closer to empirical systems. Therefore, it is still a valuable model.

17.3.2.3 A Mixed Strategy Approach

The question that follows from the above is if there is no such thing as a best all-purpose model and ecologists build models that serve different epistemic aims, is

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[10] As Taylor (2000) suggested, accessory conditions are very easily overlooked; however they are actually what makes modelling possible. Such conditions in the case of ecology may assume, for example, a uniform and constant environment in space and time.

there a best strategy to follow? It should be obvious so far that philosophers of ecology advocate for a kind of theoretical or pragmatic pluralism (Wimsatt 2001). As Odenbaugh (2006) established, Levins' original criticism challenged model monism in light of the simultaneous use of partially overlapping models and theories and inspired scientists and philosophers to accommodate diverse strategies (see, e.g. Cooper 2003; Taylor 2000; Vepsalainen and Spence 2000). Without delving deeper into details, in his early work, Levins was very clear, even when he critiqued the large-scale computer models of systems ecology, that there is no such thing as a best strategy: "Therefore the alternative approaches even of contending schools are part of a larger mixed strategy" (Levins 1966, p. 431).

An interesting example of this mixed strategy approach is offered by conservation biology and especially nature reserve design. In the 1960s Robert H. Mac Arthur and Edward O. Wilson set out to explore the relationship between the diversity of species—in this case the number of different species—on islands and island area (1967). Their basic assumption was that despite changes in species composition, the number of species inhabiting the island would remain in a state of dynamic equilibrium as a result of local extinctions and immigration. As Kingsland contented (2002a, b), their approach explicitly ignored historical detail for the sake of contributing a simple, general and realistic theory that would eventually produce testable hypotheses and integrate population ecology and evolutionary theory. Once the theory was published, conservationists realised that nature reserves could be seen as isolated islands among habitats changed by humans. This realisation raised the bar for ecologists, who were actually given a chance to apply their theory to actual world problems. Experimental work along with various data sets and observations were brought together to support theoretical arguments. However, the eagerness to apply theoretical arguments in conservation efforts was met with criticism. What was assumed as a premature transformation of basically untested theory to conservation principles resulted in one of the more fierce and rhetoric-dependent controversies in ecology that lasted for more than one decade (Kingsland 2002a, b; Looijen 2000). A growing rapprochement between conservation biology and operation research, already known to system ecologists, in the 1980s seemed to offer a viable alternative to reserve design. Over the past decade, this interdisciplinary collaboration has proven quite fruitful and the task of modelling complex ecological systems through extensive simulations is much facilitated by technological advances in computing. This kind of research, however, which largely belongs to the strategy of sacrificing generality for the sake of precision and accuracy in Levins' fashion, is extremely labour intensive as it requires large amounts of data. At the same time these developments do in no way deem theoretical research obsolete since computer simulations are still using classical simple population ecology models (Odenbaugh 2005). Hence, it seems that a mixed strategy approach that allows the advances of each perspective to equally contribute to conservation efforts is not only desirable but most importantly required, especially when considering adding to these challenges the intense social debates over nature conservation.

These considerations provide, to our view, interesting ways to address perennial issues related to science as a social process. Discussions about scientific controversies are a major vehicle for introducing students to the nature of science. It is our contentions, however, that students should also learn how scientists belonging to quite diverse research traditions might actually work together. The emphasis given by philosophers of ecology to accommodating diverse strategies seems to be very important in escaping a single, linear, one-actor depiction of scientific endeavours. At the same time, as highlighted by Lefkaditou (2012), these debates and their resolutions do not only attest to the need for a genuinely synthetic view and reveal the plurality of approaches in ecological research but are an integral part of how science advances. Therefore, students should always remain aware of the fact that there is not a unique, victorious body of knowledge but that theories; ontological, methodological and epistemological assumptions; research techniques; ideological commitments; and social factors are the driving forces of science.

17.3.3 Back to the Science Education Classroom

To sum up, philosophical considerations on models and modelling in ecology provide a more pluralistic story of the uses of models, expand beyond the classical prediction–explanation discussion and stress the tentative character, the context dependency and the heuristic power of models. As Odenbaugh (2005) emphasised, models in ecology are necessarily idealised, most of the time inaccurate, but may well be successful in different tasks depending on the purpose they were built for. We argue here that this view of modelling brings a very interesting twist in the science education literature that focuses on model-based inquiry and enriches the repertoire of choices for curriculum developers, science educators and students. Our view is very close to Svoboda and Passmore's (2011) account, which stresses the need for educators to cultivate a variety of modelling approaches in science and engage students in diverse modelling and reasoning activities in relation to specific theoretical or practical problems.

To this end, we also believe that an explicit exploration of the epistemological underpinnings of modelling does not only lie at the heart of the nature of science and scientific inquiry discussions but should also become an important element of classroom practice. The real challenge, however, is to find concrete problems, questions and examples that help illustrate model diversity and enable students to develop their meta-scientific thinking. This is in fact a double challenge, as it raises both instructional and developmental issues. Thus, we are asked to identify appropriate activities at appropriate educational levels.

An interesting case of model-based inquiry activities in ecology is the use of computer simulations. Indeed, various researchers have argued that computer simulations not only improve skills related to the understanding of specific science content but most importantly advance problem-solving and decision-making capabilities, while inviting students to explore possibilities, create hypothesis, interpret their results and frame theoretical claims (Akpan and Andre 1999; Serra and Godoy 2011). In this spirit, Carson (1996) used computer simulations to teach about food webs, Cook (1993) studied foraging behaviour, Korfiatis and colleagues (1999) explored the behaviour of a population system regulated by intraspecific competition and Lutterschmidt and Schaefer (1997) modelled predator–prey interactions, while Serra and Godoy (2011) explored population patterns. In most of these cases, computer simulations seem to have presented ecological concepts and models in a more exciting, engaging and interactive manner, while they have arguably improved students' computational and mathematical skills. What is more controversial, however, is whether computer simulations actually improve understanding of ecological subject matter and the role of models in actual scientific inquiry (see, e.g. Korfiatis et al. 1999). Our contention is that without explicit reference to the diverse epistemic aims of modelling, computer simulations are nothing more than a black-box approach. As a result, students may still see models as being isomorphic to phenomena, their simplifying assumptions are reified, statistical patterns are mistaken for causes and the fixation on predictive value as a model's true virtue goes unquestioned, while their tentative and contextual character remains untouched. Despite our best efforts, modelling and issue knowledge may well remain decontextualised.

In this spirit, Hovardas and Korfiatis (2011) have outlined an educational intervention of model-based inquiry for secondary school students that combined philosophical considerations with computer simulations. The model that students had to work with was originally introduced by the animal ecologist Walder C. Allee in 1931 to describe the negative effects that under-crowding might exhibit to certain populations. The 'Allee effect', as it has come to be known, induces lower birth rates at low population densities that may lead susceptible species to extinction. Therefore, populations with dynamics that follow the 'Allee effect' present two points of equilibrium: an unstable one at a low population size and another one at a larger population size, which is characterised as stable. If the population drops below the unstable equilibrium point, it goes extinct. In contrast, when deviating around the stable equilibrium point at a larger population size, the population returns, after a while, to its former population size.

The authors used the 'Allee effect' to discuss the case of a black vulture (*Aegypius monachus*) population in a Greek nature reserve. The target of the educational activity was not only to address different patterns of balance and help students accommodate the concept of change in nature but also support them in understanding how a simple, exploratory model might work in real-world situations. Students constructed the population model using dynamic feedback model software, like STELLA, and explored population trends in the case of minor departures from both equilibrium points, especially the fragility of a population around the unstable equilibrium point and its resilience around the stable equilibrium point.[11] Based on the model specifications, students formulated new research questions and hypotheses that referred to the models' structural components or relations between structural compartments. Simulation outcomes were contrasted to expected results and possible insights for nature reserve design were discussed.

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[11] An exemplary sequence of this approach on model-based inquiry can be found here: http://scy-net.eu/scenarios/index.php/Grasp_a_Model.

Likewise, in addition to studying population dynamics of a single population and tracking its course over time, modelling software offers the opportunity for examining interactions between populations, such as prey–predator relationships. We have often invited students to elaborate on a hypothetical situation where a population of wolves and a population of deer are found in a forest. In most cases, students assume that wolves will first consume all deer and then die since they will have exhausted their feeding sources. However, after constructing a simple prey–predator model, refining its basic characteristics and running the simulation, students come to a surprising result; no population may go extinct. Instead, wolf and deer populations fluctuate in time. Thus, students are invited to reflect on their initial understandings, refine their initial research questions and explore alternative hypotheses by relaxing their original assumptions and introducing new complications like density dependence for the prey population or a saturation coefficient for the predator. Finally, we contrast the model's outcomes with data available from empirical research and discuss how and why the model fails to match the data and possible ways to introduce more realistic assumptions.

All in all, instead of giving students finite definitions about models, it seems more appropriate to reinforce their sense-making mechanisms by introducing them to some initials questions and trying to build our models from there on. For example, we could ask: *Given the essential complexity of biological systems, how do we decide what is relevant to include in our model? When do our abstractions, simplifications or assumptions lose their legitimacy? Is it possible for a non-accurate or unrealistic model to give predictions? What else can we do with a model? If we change the range of a model's application, do the generalisations produced still hold? When do our models become old and require revision?* Of course this is only the beginning of an enduring and demanding process that requires both time and guidance.

Finally, we agree with Taylor (2000) that the emphasis on the process of modelling instead of models themselves introduced by Levins and further developed by philosophers of ecology brings a whole set of exciting new questions about scientific inquiry and its social implications. These questions are so close to the nature of science and scientific inquiry core themes that they open new paths for ecology education. We strongly believe that these are highly promising paths worth pursuing.

17.4 Conclusion

In this paper we have tried to give a glimpse of the way scientific inquiry is conducted in ecology. It is an integrative, interdisciplinary field of research encompassing a variety of theoretical frameworks and a plurality of methodological approaches. We suggest that recognising the fact that scientists use diverse inquiry methods, which serve different epistemic roles, will not only bring classroom instruction closer to actual scientific practice but will also widen the repertoire of available instructional protocols. We hope that our discussion will enrich the ongoing dialogue about the important differences among scientific disciplines and will fruitfully contribute to enhancing ecology education.

Ecology education has the difficult task of teaching students the structure and function of the world's ecosystems as well as their interrelations with humanity. Understanding the practices of ecologists is an important means towards the accomplishment of this task (Bowen and Roth 2007).

The rapprochement between history and philosophy of science and science education has opened new avenues for intellectual work. We gladly accept the challenge to find ways in which the lively philosophical and historical discussion in ecology can inform educational practice. Towards this end, we believe that the historical and philosophical considerations addressed in our work should help establish a 'progressive', or 'bottom-up', curriculum approach, as it has been outlined by various authors (Barker and Slingsby 1998; Berkowitz et al. 2005; Korfiatis and Tunnicliffe 2012; Magnetorn and Hellden 2007; Slingsby and Barker 2005).

Within such an approach, educational interventions should start with direct contact with individual elements like single species, continue with the study of their relationships and conclude with the study of processes at the level of the whole community or ecosystem. Authenticity in ecology education has no meaning without field experiences. First-hand study of the natural world should be the main part of education, especially in the pre-school and early schooling years (Korfiatis and Tunnicliffe 2012). This approach is not restricted to the study of isolated parts of a system, but it focuses on the way individual parts interact and function in forming the whole. We agree along with various other scholars that a 'bottom-up' approach could actually prove more helpful for young students trying to comprehend how a system is constructed, how its properties emerged and how structure interplays with function and behaviour (Demetriou et al. 2009; Magnetorn and Hellden 2007). The trap of oversimplification is avoided and at the same time the foundations for understanding more abstract representations of species and ecosystems are laid.

Indeed, abstract concepts, such as food webs, can be easily grasped by early primary school children if their teaching is based on the study of organisms living in, for example, the pond or the lawn of the local park and the ways in which such organisms cover their trophic needs. Gradually, modelling activities and simulations can be essentially integrated in parts of the curriculum, allowing for larger degrees of theorising and comprehension of the methodological approaches, the explanatory patterns and the nature of the science of ecology. Besides, students, especially those in higher grades of education, can be engaged in various sorts of ecological theorising, like model building. According to an ecological portrayal, scientists utilise a number of models that embody the theoretical knowledge to which they adhere. Since general theories consist of families of models, they very rarely rise or fall based on tests of any one model. Alternative or competing models exist within most theoretical constructs in ecology allowing a single theory to encompass a diversity of phenomena (Scheiner and Willig 2011). Although it is considered one of the main aims of current education, this kind of conceptual inquiry is generally missing from science classes (NRC 2012).

Within the educational process, long-term open experimental settings, such as terrariums, are important for observing and comprehending ecological processes' roles (e.g. role of decomposers), carrying at the same time a higher perceivable educational value rather than conducting ecological experiments in a hypothesis-testing, single-lesson manner. As Tomkins and Tunnicliffe (2001) note, a "project-like" approach, with long-stay instalments, starting with observations and integrated previous knowledge, allowing for multipurpose activities and an open agenda, seems to be more proper for ecology's teaching and learning.

Needless to say that within such a framework, the need for a thorough reconsideration of educators' professional development is emerging. Such a teaching transition presupposes a considerable shift in the planning of learning activities and their orchestration in order to maintain focus on learning goals and provide scaffolds when needed. To cope with the instructional challenges that are implied in the proposed reorientation of ecological curriculum, preservice and in-service teachers engaged in ecology education at the primary and secondary education level have to commit themselves to an ongoing professional development programme in the areas of outdoor education and model-based learning.

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Part V
Pedagogical Studies: Earth Sciences

Chapter 18
Teaching Controversies in Earth Science: The Role of History and Philosophy of Science

Glenn Dolphin and Jeff Dodick

18.1 Teaching Controversies in Earth Science: The Role of History and Philosophy of Science

“Battle heats up over Alaskan petroleum reserve” (National Public Radio News, July 17, 2011), “Group ends call for hydro-fracking moratorium” (CBC News, 7 July 2011), “Greenpeace report links western firms to Chinese river polluters” (Guardian, 13 July 2011), “Climate change and extreme weather link cannot be ignored” (Dominion Post, 14 July 2011), and “‘Jury Is Out’ on Implementation of Landmark Great Lakes Compact” (New York Times, 14 July 2011)—headlines such as these are an everyday occurrence. The articles themselves not only inform us about the issues concerning the planet on which we live but also indicate the economic, political, and social influences/implications inexorably tied to them. It is reasonable to assume that a certain “working knowledge” of the systems of earth is necessary for one to be able to understand the issues as they are and even more so if one would want to make informed decisions (personal, political, social, or economic) related to such issues. This especially holds true for the current generation of K–12 students. They are the citizens of the future and should be

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prepared with the education needed to intelligently evaluate circumstances with potential adverse environmental impact. Hoffman and Barstow emphasized this in their call to action:

> Understanding Earth's interconnected systems is vital to the future of our nation and the world. Ocean and atmospheric interactions effect our daily lives in multiple, significant ways. Long-term changes in ocean and atmospheric processes impact national economies, agricultural production patterns, severe weather events, biodiversity patterns, and human geography. Global warming and its effects on glacial mass balance, sea level, ocean circulation, regional and global weather and climate, and coral bleaching, to name only a few potential impacts, are important global issues that demand immediate attention. (Hoffman and Barstow 2007, p. 9)

This general philosophy is borne out in the National Science Education Standards (NSES) (NRC 1996, 2012). The NSES have placed an equal emphasis on the teaching of Earth and Space Science (ESS) as has been given physics, chemistry, and biology. We direct the reader's attention to very recent works, such as the Next Generation Science Standards (NGSS) (Achieve, Inc. 2012) and the Earth Science Literacy Principles[1] (Earth Science Literacy Initiative 2010). The NGSS give an example of the emphasis placed on geoscience education by way of both the disciplinary core ideas and the crosscutting relationships, while the Earth Science Literacy Principles delineate nine big ideas in the geosciences as a framework of what a literate citizen of the USA should know within the domain of earth science. However, in the past several decades, ESS teaching has been struggling to keep pace with teaching in the other sciences. Currently, only about 7 % of US high school students have taken a course in ESS, and there are just over 10,000 earth science teachers at the secondary level in the USA, compared to about 52,000 for biology (Lewis and Baker 2010). In her review of the education research literature focused on earth science conceptions, Cheek (2010) found only 79 empirical investigations published between 1982 and 2009. Our search for investigations focused on the use of history and philosophy of science (HPS) in teaching earth science yielded fewer than 20. In this book alone there is only one earth science chapter compared to the six for physics and three each for biology and chemistry. With these statistics in mind, it is obvious that there is a need to (1) increase the number of students taking ESS classes at all levels of schooling, (2) increase the number of earth science majors graduating from universities, (3) increase the number of highly qualified earth science teachers, and (4) enhance the quantity and quality of earth science education research (and especially in the field of HPS use in teaching earth science). We hope this chapter will be a small stepping-stone toward this goal.

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[1] The nine ESLP big ideas are as follows: 1-earth scientists use repeatable observations and testable ideas to understand and explain our planet; 2-the earth is 4.6 billion years old; 3-the earth is a complex system of interacting rock, water, air and life; 4-earth is continuously changing; 5-earth is the water planet; 6-life evolves on a dynamic earth and continuously modifies earth; 7-humans depend on earth for resources; 8-natural hazards pose risks to humans; and 9-humans significantly alter the earth.

Cheek (2010) pointed out that in general, students' understandings of geoscience concepts have not improved over the past several decades. She did assert that we know more about students' geoscience conceptions than we did 27 years ago and now we need to utilize that information to enhance instruction. Efforts to do just that have included utilizing an earth systems approach where the main focus of instruction is to develop students' understanding of the four different *spheres* (geo-, bio-, hydro-, and atmo-) and how they influence and are influenced by each other (Rankey and Ruzek 2006). Earth science by design (ESbD) (Penuel et al. 2009), an extension of Wiggins and McTighe's (2005) work, is an approach whose goal is to achieve enduring understanding through teaching about earth via a few *big ideas*.

Another seemingly fertile approach, though underutilized, has been the incorporation of HPS within instruction, with emphasis on the many controversies experienced throughout the history of the earth sciences (Bickmore et al. 2009b; Montgomery 2009). By HPS, we are referring to the many factors that influence the progression of scientific understanding. This may include economic, political, or social factors. It also encompasses philosophical considerations which oftentimes are responsible for directing investigations and discerning observational data from the "noise." These philosophical differences may form the basis of controversy as well. For our purposes we will use Venturini's definition of controversy:

> Controversies are situations where actors disagree (or better, agree on their disagreement). The notion of disagreement is to be taken in the widest sense: controversies begin when actors discover that they cannot ignore each other and controversies end when actors manage to work out a solid compromise to live together. Anything between these two extremes can be called a controversy. (Venturini 2010, p. 261)

The history of the geosciences is rife with controversial issues such as how marine fossils could be found at mountain tops (Cutler 2003), plutonism versus neptunism (Repcheck 2003), "uniformitarianism" versus "catastrophism" (Şengör 2001), deep time and the age of earth (Repcheck 2003), hollow earth theory, contracting earth theory (Oreskes 1999), the use of fossils to date rocks (Rudwick 1985), expanding earth theory (Adams 2005), continental drift versus land bridges (Oreskes 1999), the theory of plate tectonics (Oreskes and LeGrand 2001), dinosaur extinction (Alvarez and Chapman 1997; Glen 2002), the "current and heated" controversy concerning plume theory (Anderson and Natland 2005; Anderson 2006; Glen 2005), as well as the ever-present conflict between science and religion (Bickmore et al. 2009a). Instructors have found that "teaching the scientific controversy" has been effective at garnering interest from students, enhancing their critical thinking skills, not just in the geosciences[2] but also physics (De Hosson and Kaminski 2007), chemistry (Justi 2000), and biology (Seethaler 2005).

Researchers have also found that incorporating HPS within instruction helps to augment students' understandings of the nature of science (NOS) as emphasized in the NSES (NRC 1996, 2012). The use of HPS as an instructional tool was written

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[2] For examples, see Dolphin (2009), Duschl (1987), Montgomery (2009), and Pound (2007).

about as early as the mid-twentieth century (Conant 1947). Conant emphasized the importance of students understanding the "tactics and strategy" of science. The other efforts of infusing HPS into instruction, such as Harvard Project Physics and the BSCS Biology, also deserve accolades (Matthews 1994/2014). Matthews also stated that teaching with HPS is important because it promotes better comprehension, is intrinsically interesting, counteracts scientism and dogmatism, humanizes the process of science, and connects with disciplines within science as well as outside of science, and historical "learning" reflects individual learning about concepts. Many others have written in favor of the use of HPS within science instruction.[3]

In this chapter, we will situate the geosciences philosophically and methodologically with respect to biology, chemistry, and physics. We will highlight four different geoscience concepts and their related controversies, including what we know about the use of HPS for teaching these concepts, what has been done, and what, in our minds, is still in need of being done. We will offer pedagogical, cognitive, and historical rationales for the use of controversy in teaching earth science concepts, and we will organize our discussion of controversies within the context of the four spheres of the earth—geosphere, biosphere, hydrosphere, and atmosphere. Though highlighting a particular domain within the geosciences, each phenomena surrounded by a historical and philosophical controversy will also exemplify its global nature in terms of its influence. The controversies described below are those surrounding the acceptance of plate tectonics as the grand unifying theory of earth (geosphere controversy); the meteorite impact theory explaining the Cretaceous–Paleogene (or K–Pg) mass extinction (no, it was not just dinosaurs that went extinct) (biosphere controversy); the connection of rhythmic long-term weather variations in various parts of the world to oceanic temperature in the tropical Pacific Ocean, also known as ENSO (hydrosphere controversy); and finally, the current controversies surrounding the acceptance of anthropogenic global climate change (**ACC**) (atmosphere controversy).

18.2 Nature of the Earth Sciences

What is the nature of the earth sciences? How are they, as disciplines, distinguished from other sciences? Some might be surprised that these questions are even being posed, as they seem so basic. However, we believe that these questions need answers for several reasons. Unfortunately, for much of the last century, the earth sciences have been portrayed as derivative disciplines whose logic and methodology were furnished by the physical sciences. Indeed, the history of the earth sciences is annotated by episodes where not only physicists but even (surprisingly) some geologists tried to reconstitute the earth sciences as a tributary of physics (Dodick and Orion 2003).

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[3] See, for instance, Allchin (1997), Bickmore et al. (2009b), Justi (2000), Matthews (1994/2014, 2012), and Rudolph (2000).

This trend has continued into recent times such that Gould (1986, 1989) noted that some scientists do not accept the methodological diversity of the sciences and specifically disparage the earth sciences as being less scientific than the physical sciences.

Unfortunately, this message that the earth sciences are derivative has been reinforced by work in the history and philosophy of science (HPS). For much of the twentieth century, the classic works of HPS emanated from scholars (Popper, Kuhn, Lakatos) who largely relied on examples from physics to illustrate their discussions, a critique which has been mentioned by others.[4] In fact, even in the small number of philosophical works that have examined their nature, the earth sciences have been declared as either derivative or at least as not unique sciences.[5] It is only in the last 30 years or so that this lack has been redressed, as witnessed by the increased number of tomes connected to HPS works dedicated to the earth sciences, as well as the publication of *Earth Sciences History*, the only academic journal exclusively devoted to the history of these disciplines.

Unfortunately, such work has not penetrated into the world of education, such that some science educators are often left with the impression that the earth sciences are less rigorous than the physical sciences and thus less worthy of being taught as part of the standard science curriculum (Dodick and Orion 2003). Such thinking is mistaken because it does not consider the special nature of the earth sciences as one of the historical and interpretive (or hermeneutic) sciences (Frodeman 1995; Orion and Ault 2007) which classically attempt to reconstruct past phenomena and processes by collecting their natural signs during fieldwork. This nature is shared to a large degree with other historical fields such as evolutionary biology and astronomy (Cleland 2001, 2002). Concurrently, it contrasts with experimental sciences such as physics or molecular genetics in which natural phenomena are manipulated within the controlled environs of a laboratory in order to test a hypothesis. Indeed, the differences between these two groups of science are derived from the fact that the historical sciences, such as the earth sciences and evolutionary biology, developed specific methodologies to cope with problems that could rarely be tested under controlled laboratory conditions.[6]

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[4] See, for instance, Baker (1996), Frodeman (1995), Greene (1985), and Mayr (1997).

[5] See, for instance, Bucher (1941), Goodman (1967), Schumm (1991), and Watson (1969).

[6] We do not mean to imply that the earth sciences are devoid of experimentation. Indeed, whole fields within the earth sciences including geophysics, geochemistry, and climate science have tested some of their claims using cutting-edge experimental methods which produce important research results. Philosophical classifications sometimes simplify, ignoring the overlap that occurs between categories, and this is the case in the historical–experimental dichotomy we use in this chapter. We still believe that it is a fruitful classification as many philosophers and historians of science have used it in their definition of different sciences (See Dodick et al. 2009 for a review of the development of the term *historical sciences*). Moreover, one of us (Argamon et al. 2008; Dodick et al. 2009) has tested this dichotomy empirically and has indeed found that the earth sciences (representing diverse fields including geology, geochemistry, and paleontology) do fall more regularly into the historical science category.

Table 18.1 Methodological contrasts between the experimental and historical sciences

Dimension	Experimental	Historical
Research goal	General laws and behaviors	Explanations for ultimate and contingent causes
Evidence gathered by	Controlled manipulation of nature	Observing/analyzing preexisting entities and phenomena
Hypotheses are tested for	Predictive accuracy	Explanatory accuracy
Objects of study	Uniform and interchangeable entities	Complex and unique entities

Recently, a growing number of scientists, philosophers, and educators have critiqued the idea of there being a universal scientific method largely emanating from the experimental-based, physical sciences[7] and instead promoted the view that different combinations of logic and methods can and should play different roles in different disciplines. Indeed, one of us has empirically tested such claims by analyzing the pattern of language use in the historical and experimental sciences, respectively; the results of this work show (statistically) significant variation in language use between the two groups of sciences that are derived from the specific methodologies employed by these two groups of sciences (Argamon et al. 2008; Dodick and Argamon 2006; Dodick et al. 2009).[8]

This following discussion will review this empirical work to provide the reader with a better understanding of the methodological differences between the historical and experimental sciences. By doing this, we also create a philosophical framework for analyzing the historical controversies that we present later in this chapter. Table 18.1 presents four methodological contrasts between historical and experimental sciences which will be used in this discussion.[9]

The ultimate *research goal* of the experimental sciences is a general statement or causal law that is applicable to a wide variety of phenomena in many contexts (Kleinhans et al. 2005). To achieve this goal, *evidence is gathered* via controlled experimentation within laboratories in which the natural phenomena are manipulated to test a facet of a theory or hypothesis (Case and Diamond 1986). The quality of such a *hypothesis is tested* by the consistency of its predictions with the results of its experiments. Finally, the form of such experimental research is dictated largely by the fact that it is conducted on uniform and interchangeable *objects of study*, such as atoms; the fact that such entities are uniform, or nearly so, makes the formulation

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[7] See, for instance, Cartwright (1999), Cleland (2001, 2002), Cooper (2002, 2004), Diamond (2002), Dodick et al. (2009), Frodeman (1995), Gould (1986), Kleinhans et al. (2005, 2010), Mayr (1985), and Rudolph and Stewart (1998).

[8] These studies encompassed a series of experimental fields including physical chemistry, organic chemistry, and experimental physics; historical fields included paleontology, geology, and evolution.

[9] This section is arranged to correspond with the ordering of Table 18.1. The dimension under consideration is delineated in italics.

of general laws possible in principle and experimental reproducibility a reasonable requirement in practice (Diamond 2002). This desire for reproducibility means of course that results of a given experiment should be uniformly reproduced, given the same conditions, in any laboratory in the world; this result fulfills one of the basic principles of science, the principle of uniformity of law (Gould 1965, 1987).

In contrast, the *research goal* of historical sciences, such as the earth sciences, is to uncover ultimate and contingent causes buried in the past whose effects are interpreted only after very complex causal chains of intervening events (Cleland 2001, 2002). Accordingly, *evidence is gathered* by observation of naturally occurring signs exposed during fieldwork, since controlled experimental manipulation is usually impossible due to the fact that the historical sciences are interpreting cause and effect in past events that cannot be repeated or replicated; in fact, even if this were possible, the enormous amount of time, space, and the complex relationship of variables needed to affect the result would inhibit such scientific research from happening.

Such observation is not a passive act of simply looking, or searching for evidence, as the word "observe" might imply to those unfamiliar with the earth sciences. This is due to the fact that such evidence is often hidden in time and space from an earth scientist. Instead, such observations are guided by deep inferences and intuitions about earth processes that are developed by earth scientists through long periods of exposure to field materials.[10]

When possible, rather than making observations on a single entity (such as an outcrop), historical science relies on natural experiments (Case and Diamond 1986; Diamond 2002).[11] Natural experiments are based on analyzing the effects of natural (i.e., not manipulated by the experimenter) perturbations in the field. In implementing such studies, the researcher must also choose at least one "control" site, which is similar to the experimental site, but that lacks the same natural perturbations. Unlike laboratory experiments, natural experiments do not control their independent variables due to the confounding complexity of field conditions.

This focus on past causation in historical sciences implies that the ultimate *test of* (the quality of their) *hypotheses* is explanatory adequacy via retrodiction of specific past events rather than prediction as in experimental sciences[12]; this is due

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[10] In the past earth scientists were restricted to physically uncovering hidden field materials; this of course restricted their research to areas to which they had access. However, technology has revolutionized this search, for example, tools, such as remote sensing via satellite makes the invisible visible, both here on earth, as well as on other planetary bodies.

[11] Diamond and Robinson (2010) have also documented how natural experiments are also applied within the humanities and social sciences where controlled experimentation is impossible.

[12] As Schumm (1991, p. 7) notes, the term prediction in science is used in two ways: "The first is the standard definition to foretell the future. The second is to develop a hypothesis that explains a phenomenon." Based on the second definition, such predictions have the typical form of: "if a given hypothesis is correct then we predict that the following process or phenomenon will occur." In the case of experimental sciences, both definitions are methodologically applicable. Schumm (1991) argues that in some fields of earth science (e.g., geomorphology), prediction to the future (i.e., the first definition), based on extrapolation, is also part of their current methodology.

to the fact that the *objects of study* in historical sciences such as the earth sciences are complex, unique, and contingent, with very low chances of repeating exactly (Kleinhans et al. 2010). This methodological need places great stress upon earth scientists' powers of "retrospective thinking," in which they apply knowledge of present-day processes in order to draw conclusions about processes and phenomena that developed millions of years ago (Orion and Ault 2007), a methodology that the historical sciences terms actualism.[13]

The methodology of such explanatory reasoning derives from what Cleland (2001, 2002) calls the "asymmetry of causation," in that effects of a unique event in the past tend to diffuse over time, with many effects being lost and others confused by intervening factors. Making sense of such complexity requires, therefore, synthetic thinking (Baker 1996), in which one fits together complex combinations of evidence to form arguments for and against multiple working hypotheses (MWH) which often compete with each other.

In addition to sifting through the complexity of processes, earth scientists must also deal with the complexity of the physical entities they study. Unlike subatomic particles, for example, which are all uniform, the individuals studied by earth scientists—fossils, strata, igneous intrusions—are all unique (though often similar) individuals, whose precise form and function cannot always be reconstructed. This usually removes the chance of formulating universal laws and allowing only statistical explanations of relative likelihoods at best, so that arguments for and against multiple hypotheses must be made on the preponderance of the best evidence.

Even so, we argue that such predictions are far less common and accurate in historical sciences, than they are in experimental sciences, in large part due to the complexity of the phenomena studied in such disciplines; instead, historical science focuses on reconstructive explanations, via the method of retrodiction, which might be defined as a specification of what did happen (Engelhardt and Zimmermann 1988; Kitts 1978). As Ben-Ari (2005, p. 15) notes "retrodiction is essential if theories are to be developed for the historical sciences." Indeed, Schumm (1991) admits that it is only when the present conditions are understood and when the history of the situation has been established that predictions to the future (i.e., the first definition) can be made with some degree of confidence in earth science. In other words, in historical-based sciences, such as the earth sciences, reconstructing past conditions takes precedence and as a method has greater validity than predicting the future.

[13] In defining actualism, some philosophers and geologists separate between two definitions of the earth sciences most important, but most misunderstood concept, uniformitarianism (Hooykaas 1959; Gould 1965, 1987; Rudwick 1971).

Substantive uniformitarianism or sometimes uniformitarianism claims that geo-historical uniformity exists between present and past geological phenomena, such that the force, rates, and types of phenomena do not change over the course of geological time.

Methodological uniformitarianism or simply actualism is a method permitting an earth scientist, via analogical reasoning, to explain the geological past based on geological events observed in the present. On the basis of these observations, geologists make inferences about the types of causes and their force in the past.

These two types of uniformitarianism were conflated together by Lyell (Gould 1984, 1987) which has led to some of the modern-day confusion of the term uniformitarianism. We will discuss the impact of Lyell's conflation when we discuss the case study concerning the Cretaceous–Paleogene extinctions.

Thus, reasoning about the relative likelihood of different assertions is endemic to the synthetic thinking patterns of historical science.

As can be seen, inquiry within the earth sciences cannot guarantee reproducible results over space and time like the experimental sciences. Indeed, the very purpose of the earth sciences is to explain the unique, contingent, and complex systems acting over the entire earth and its interacting "spheres" (geosphere, hydrosphere, atmosphere, and biosphere) as well as analyzing their subsystems on more local scales (Orion and Ault 2007).

This concern for global complexity can and should be used as a tool of science education because it prevents the earth sciences from being portrayed as what Allchin (2003) terms a science of *myth-conception*. By myth-conception, Allchin (2003) is referring to a narrative device which embodies a "world view that provides formulae or archetypes for appropriate or sanctioned behaviour." For example, the history of science has sometimes portrayed discoveries as the efforts of a single, idealized scientist. Even the names used to describe these discoveries support these impressions: "Mendelian genetics," "Darwinian evolution," and the "Copernican revolution."

Such idealized portrayals of science sometimes occur because its narrative is shaped by "sharpening" what is considered the central message, while "leveling" the details thought to be less central (Allchin 2003). Moreover, science is often considered as a problem-solving endeavor in which the goal is to get the single, right answer; this has sometimes infected its philosophy, such that the questions that have been asked ("What is the method of science?" or "How does science advance?") focus on a single process (Oreskes 2004) As Oreskes (2004) argued, many academic fields, including history, art, and literature, embrace multiple perspectives as they analyze a problem and so in fact do the sciences. Nowhere is this more evident than in the earth science paradigm of plate tectonics, which embraces multiple conceptual tools including experimentation, mathematical models, novel instruments, analogical reasoning, and visualization. Equally important, plate tectonic theory synthesized huge amounts of data that were collected by many scientists, working on independent problems, and scattered over the entire earth. Indeed, without such global efforts the theory would have never been accepted. Concurrently, this global effort has meant that plate tectonics have not acquired the attached name of one archetypical scientist. Thus, it is the perfect scientific theory for demonstrating the nature of science to students. As we will show, plate tectonics is not unique, and all of the controversies that we will be exploring in this chapter also demonstrate this global nature of the earth sciences.

18.3 Why Controversies?

We believe that framing the learning of the earth sciences in historical controversies is justified from the perspectives of the learning sciences, as well as the history and philosophy of science.

From the perspective of the learning sciences, it is well known that students (up to and including their university years) are often epistemological dualists, viewing academic issues in terms of true or false, right or wrong, credit or no credit (Alters and Nelson 2002). At first glance this poses some dangers to the deeper critical thinking skills that we want students to develop. This assertion is also sometimes reinforced, ironically, by popular misinterpretations of the conceptual change movement which often sees "mis"conceptions as entities to be uprooted and so to be replaced by the final "correct" conception. However, the progenitors of the conceptual change movement themselves, Posner and his colleagues (1982), noted in their original article that conceptions, for the good and the bad, are important scaffolds that lead to further conceptual development. Moreover, diSessa and his colleagues (diSessa 1988; diSessa 1993; Smith et al. 1993) in their works on "learning in pieces" emphasized that ideas perceived as misconceptions have a heuristic potential that allow them to do important conceptual work; the key is for the student and scientist to know the limits of validity connected to such conceptions.

More recently, Marton et al. (2004) have outlined a theory of learning that connects perfectly with the comparative nature of controversies. The key facets of this theory are the "object of learning," "variation" between objects of learning, and "the space of learning." The object of learning is the concept that is to be learnt in a given lesson. From the teacher's perspective, the goal of the lesson is to present an intended object of learning, which through the discourse of the lesson becomes the enacted object of learning or what is possible to learn in the lesson. Finally, from the learner's point of view, what is actually learnt is termed the lived object of learning. The key way in which the object of learning becomes enacted is through the teacher's use of variation. In other words, according to Marton and his colleagues, learners can only learn an object when it is presented in comparison to something with which it differs. For example, if the objects of learning are the colors green and red, learners who are color-blind will not be able to see the difference between these and, therefore, opportunities for them to learn will not be available. These variations create a space of learning which refers to what is possible to learn in that particular situation. This space is largely created through language.

Finally, the idea of controversy connects perfectly with the recent movement toward using argumentation as an important component of classroom discourse. Veerman (2003, p. 118) succinctly summarized the value of classroom argumentation when he noted that, "in argumentation…knowledge and opinions can be (re)-constructed and co-constructed and expand students understanding of specific concepts or problems." Moreover, argumentation dovetails perfectly with *inquiry*-based learning in which students replicate what scientists do when they are pursuing an authentic scientific problem, as research programs can be viewed as large-scale arguments supporting and falsifying different theoretical frameworks.

Controversies also align with the history and philosophy of science, both on a general level and a specific level. On the general level, we reference the educational philosopher Joseph Schwab (1964) who argued that all too often, students merely learn the facts and final outcomes of scientific research, what he called the "rhetoric of conclusions." This is certainly the case in many textbooks where one scientist's conception is simply shown to replace a previous scientist's conception, without a deeper reference to the many factors that influenced this development. Gould (1987) labeled this as "cardboard" history because of its two-dimensional nature. In response, Schwab (1958, 1962, 1963, 1966, 2000) promoted the *science as inquiry* model. Recognizing that students should come to understand how scientists interpret information and form ideas, Schwab stressed the idea that proper science education should show how these products were derived by scientists—how a body of knowledge grows and how new conceptions come about. To achieve this goal, Schwab emphasized the use of history of science including the reading of original papers and historical narratives exposing the developmental path of scientific concepts (Schwab 1963). The use of historical controversies connects perfectly with Schwab's philosophy, because properly constructed, such controversies can also teach about the complex pathways in the development of scientific concepts.

On a specific level, the idea of controversies strongly aligns with one of the key methods in geology, "multiple working hypotheses" (MWH), which were most prominently elucidated by Gilbert (1886), Chamberlin (1890/1965, 1897), and Johnson (1933).[14] Although mentioned in a previous section of this chapter, we will expand this discussion as MWH has importance both for the general structure of the earth sciences, as well for its connections to controversies.

Chamberlin (1965, p. 755–756) recognized three phases in the history of intellectual methods. The first phase was based on the *method of the ruling theory* where a "premature explanation passes into a tentative theory, then into a theory, and then into a ruling theory." This linear process, in Chamberlin's opinion, was "infantile" for the reason that only if the tentative hypothesis was by chance correct does research lead to any meaningful contribution to knowledge. Less problematic, in his view was the second phase based on a *working hypothesis*, which is a hypothesis to be tested, not in order to prove it but rather as a stimulus for study and fact finding ("ultimate induction"). Nonetheless, a single working hypothesis can unfortunately be transformed into a ruling theory, and the need to support the working hypothesis, despite evidence to the contrary, can become as strong as the need to support a ruling theory. Chamberlin therefore suggested his third phase, based on *MWH*, which was thought to mitigate the danger of controlling ideas. It did so because the investigators develop many hypotheses that might explain the phenomena under study. This was done prior to the actual research and hypotheses were oftentimes in conflict with each other.

Both Blewett (1993) and Johnson (1990) have criticized MWH based on its logic and practicality, respectively. However, as Baker (1996, p. 207) has argued, such criticism occurs "within the context of our times." Thus, for example, Blewett's critique was largely based on a "physics-based philosophy of science." Baker, however, suggested that we look at what MWH meant when it was first formulated. First, it was intended as a method for "naturalists" (whose work was conducted in the field) and not mathematical physicists (who were lab-based experimentalists).

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[14] Additional work was provided by Gilbert (1896), Chamberlin (1904), and Davis (1911).

Second, the purpose of MWH was, in Chamberlin's view, to facilitate certain "habits of mind" which were of special concern to naturalists generally and geologists specifically. This second purpose certainly integrates with the goals of science education in which we try to open students' scientific worldview to alternatives, as they often stubbornly (as epistemological dualists) adhere to a single conceptual framework.

This of course does not mean that the experimental sciences do not avail themselves of MWH. Indeed, Platt (1964) reported on the use of such a method in both molecular biology and high-energy physics, both of which are definitely experimental in nature. Moreover, he advocated its use, which is part of a larger method he termed "strong inference" in other sciences, for its ability to bring rapid research advances. However, this does not necessarily mean that such experimental fields need to avail themselves of MWH. A more linear process of testing single hypotheses is possible and is still followed in many laboratories.

In the case of the earth sciences, MWH has a practical value even today for its practitioners. As earth science is often conducted in the field (or with materials that must be collected from the field), it focuses on complex natural systems, which are often the result of several irreducible causes, and the application of MWH makes it more likely that a scientist will see the interaction of the several causes. Moreover, from a practical perspective MWH has value because earth scientists conduct periodic stints of fieldwork (unlike laboratory scientists who have full-time access to their lab-based experiments). This means that it is critical to test multiple hypotheses when they have direct access to their primary data (Blewett 1993).

18.4 Highlighting the Four Controversies

We will turn our attention, now, to the four case studies of scientific controversy that we wish to highlight in this chapter. Those controversies are those surrounding the development of the theory of plate tectonics, the impact theory of mass extinction at the end of the Cretaceous, the El Niño Southern Oscillation (ENSO) theory of control over long-term weather, and the current controversy surrounding anthropogenic climate change (ACC). We discuss these four cases for a number of different reasons.

First, the concept at the center of each case study is popular, in that each have been in the popular media fairly recently and both scientists and the general public should have some familiarity with them. Second, each phenomenon has, or has had an impact that reaches a global level, influencing all systems of the earth. Plate tectonics, for instance, is considered the grand unifying theory of the earth. We have designated it as a phenomenon that occurs within the geosphere. However, its impacts reach into oceanic composition and circulation, planetary wind patterns, and selective evolutionary pressures. Third, each of the case studies highlights nicely the history and philosophy of the geosciences. That is, they utilize methods that emphasize earth science's historic and interpretive nature as discussed earlier in this chapter.

In each case, scientists observed an entity or phenomenon's "end product," such as a mass extinction, a mountain range, or anomalous weather conditions. They had to discriminate among a multitude of possible and complexly related variables to determine causation. In the quest for contingent causes, they built models and then looked back in history for explanatory accuracy. This is not to say that each of these episodes played out in the same way as any of the others. It is through our framing of the controversies that we draw out similarities.

18.5 Geosphere: The Acceptance of Plate Tectonics as the Grand Unifying Theory of the Earth

The history of thoughts concerning the origins of continents and ocean basins is a long one, starting before biblical time right up through the present. A comprehensive treatment of this topic is out of the scope of this chapter but can be found in Şengör (2003) for those who are interested. This section demonstrates the general structure of geology as it pertains to the development of the theory of plate tectonics. As with the other controversies discussed in this chapter, this section displays the global nature of the phenomenon under investigation. Although there is a long history on this topic, we begin the story of the development of the theory of plate tectonics with the introduction of the theory of continental drift in 1912 by Alfred Wegener (Wegener and Skerl 1924). At this time, there were multiple varied (and contradictory) working hypotheses to explain the dynamics of the earth. As described by Alexander Du Toit, geologists considered that

> geosynclines and rift valleys are ascribed alternatively to tension or compression; fold-ranges to shrinkage of the earth, to isostatic adjustment or to plutonic intrusion; some regard the crust as weak, others as having surprising strength; some picture the subcrust as fluid, others as plastic or solid; some view the land masses as relatively fixed, others admit appreciable intra- and intercontinental movement; some postulate wide land-bridges, others narrow ones, and so on. Indeed on every vital problem in geophysics there are…fundamental differences of viewpoint. (Du Toit 1937, p. 2)

Specifically, by the end of the nineteenth century, there were two different models for earth dynamics relying on the thermal contraction of the earth. Edward Seuss hypothesized that the crust of the earth was homogeneous and allowed for continents and ocean basins to be interchangeable. Basins were places where contraction left room for the collapse of large areas of crust. James Dana, on the other hand, saw a difference in the composition between ocean crust and continental crust where ocean crust was denser and therefore sank further into the earth. The implication of Dana's contraction theory is that continents and oceans are permanent, or "fixed," entities on the earth's surface. Ironically, though Wegener's theory reconciled many of the controversies noted by Du Toit, it was for that very reason, and some others as well, that it faced an uphill battle for acceptance, especially for North American scientists (Oreskes 1999).

A meteorologist and cartographer, Wegener became interested in the problem of the origin of continents and ocean basins upon noticing the similarities between coastlines of western Africa and eastern South America. Although he was not the first to notice these similarities (Hallam 1973; LeGrand 1988; Oreskes 1999), he was the first to rigorously explore lateral displacement of the continents as a causal explanation for these observations. Besides the "jigsaw" fit of the continents, Wegener "drew on several elegant lines of empirical evidence" (Glen 2002, p. 102), including such complex entities as paleontological, paleoclimatic, and geographical and geophysical effects[15] to support his argument that a supercontinent he referred to as Pangaea existed up to about 205 million years ago and began rifting apart until assuming the current continental positions.

Wegener's hypothesis received some acceptance in Europe, South Africa, and Australia. This was not the case in North America, where the idea of drifting continents and its implications did not set well with many geologists for both empirical and philosophical reasons (Oreskes 1999). Rollin Chamberlin (1928) delineated 18 arguments against the drift hypothesis. Generalizing from this list shows what the major objections were. First, Wegener provided no reasonable mechanism or force for moving continents through softer, but solid ocean crust without showing some kind of deformation. Second, geologists found Wegener's ideas to be "superficial" because he generalized his conclusion from the generalizations of others' works in paleontology, paleoclimate, and geophysics. Third and considered more important (Oreskes 1999) was that that Wegener's ideas did not seem to appeal to the philosophy of uniformitarianism, held in great esteem by geologists at the time. Part of the ability to interpret past events was to consider the natural processes to be uniform through time. Wegener's hypothesis did not show the cyclicity that had been observed in other interpretations of the past. Indeed, Chamberlin (1928) considered Wegener's hypothesis to be "a 'footloose type'"—one that "takes considerable liberties with our globe and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories" (p. 87). In the same publication Schuchert (1928, p. 140) critiqued drift stating, "We are on safe ground only so long as we follow the teachings of the law of uniformity in the operation of nature's laws."

During this time, thermal contraction and its corollary, land bridges, were not nearly as comprehensive as drift in putting observations into the context of a global phenomenon, plus contraction and land bridges had major geophysical difficulties as explanatory models. It would take about 40 more years to amass the right data to be analyzed at the right time by the right people for the idea of lateral motion of continents to gain widespread acceptance. These data would eventually come from the emerging and global studies in radiometric dating, paleomagnetism, physical oceanography, and seismology. It was not that anyone in these fields was working specifically on this question of the origin of continents and oceans. The emergent data began to converge and the lateral drift interpretation of earth's past could no

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[15] See Hallam (1973, pp. 9–21) for a detailed description of Wegner's various lines of evidence.

longer be ignored. This idea of convergence of data will be important in the controversies that follow as well.

There were two lines of investigation in paleomagnetism. One was concerned with explaining an apparent "wandering" of the magnetic poles of the earth and the other with a reversal of polarity of the magnetic field over time. Pierre Curie, in 1895, determined that as hot, iron-bearing rock cooled to below the Curie temperature (approximately 260° C), it would assume the earth's magnetic signal at that time. When measuring magnetic signals within continental basalts of different ages and from different parts of the world, geologists found that the magnetic north pole of the earth appeared to have moved through time. The only explanations for this were that either the pole had indeed "wandered" through time or the continents did or both. In the mid-1950s, Runcorn assembled "polar wandering paths" for North America, Europe, Australia, and India and compared them to each other. The paths were not parallel. This suggested, then, that the continents and not the pole did move over time (Morley 2001).

The second line of investigation looked at another phenomenon which was that the magnetic polarity observed in the rocks every once in a while showed a 180° reversal in polarity compared to the earth's current polarity. At first such an observation was ignored as being a phenomenon of the extraction process or some sort of chemical reaction within rocks of certain composition. However, as data became more global, it became obvious that rocks of the same age maintained the same polarity, whether that polarity was normal or reversed. This led researchers like Cox, Doell, and Dalrymple to consider the changing of the earth magnetic polarity to be a global phenomenon that was recorded in the rocks as it happened. Utilizing the advancements in radiometric dating, they set about constructing a timeline of magnetic reversals. Glen (1982) showed the evolution and refinement of this timeline starting in the late 1950s to 1966.

Though there was no other way to interpret the polar wandering evidence than by the drift of the continents, geomagnetism was a new field and most geologists, not really understanding it, were skeptical of the implications (Oreskes 1999). That having been said, Cox, Doell, and Dalrymple's evolving magnetic reversal scale, published through 1966, would eventually be the key to unlock the secret to earth dynamics (Glen 1982).

Meanwhile, due to world events such as WWII and the beginning of the Cold War era, the ocean basins became very important objects of investigation. Teams of researchers out of Columbia University's Lamont-Dougherty Geological Observatory (now Lamont-Dougherty Earth Observatory, or LDEO), under the guidance of Maurice Ewing, a staunch "fixist," began making observations and taking ocean crust and sediment cores from the seafloor. Results from this data collection extravaganza included Marie Tharp's and Bruce Heezen's discovery of an enormous though narrow chain of mountains running the length of the Atlantic Ocean (Heezen et al. 1959). They also observed a large rift running lengthwise down the center of this mountain chain. Other pertinent observations were a general rise in elevation of these so-called ocean ridges, high heat flow within the rifts, lower sediment thickness, and increasing age symmetrically about and away from the ridge.

In response to these findings, Hess (1962), originally a fixist, posed a contingent cause in what he referred to as “an essay in geopoetry.” Hess proposed a theory that had the mid-ocean ridges as places where hot mantle rose and pushed the ocean crust away laterally from a rift. This crust would move like a “conveyor belt” and eventually cool and be consumed as it sank and reentered the earth. His theory would later become known as the theory of seafloor spreading (Dietz 1961). At approximately this same time, former drift proponent, S. Warren Carey, proposed another interpretation, or model, to explain these global observations. His idea was that the earth, at the end of the Paleozoic era, began to grow and the solid crust of the earth began to fragment and spread apart as the earth grew to its current position today. Carey (1976) claimed his ideas were eclipsed by the idea of subducting crust which “has enjoyed meteoric rise to almost universal acclaim, and every aspiring author must jump on the bandwaggon [sic] to gild another anther of this fashionable lily” (p. 14).

Another team of geologists from Scripps Oceanographic Institute were conducting their own studies of the seafloor and discovered an unexplainable pattern of magnetic anomalies. The pattern was that of alternating parallel stripes of reversed and normal magnetism in the basalts near and parallel to the ocean ridges (Mason and Raff 1961; Raff and Mason 1961). It took Fred Vine, a physicist, trained in geomagnetism himself and sympathetic to the drift hypothesis, to combine Cox, Doell, and Dalrymple’s magnetic reversals timeline with Hess’ verses of geopoetry to answer the question of the “zebra stripe pattern” on the seafloor (Vine and Matthews 1963). Coincidentally, and independently, Canadian geologist Lawrence Morley, also trained in magnetism, saw the Raff and Mason paper and a paper about seafloor spreading (Dietz 1961) and had a similar “eureka” moment (Morley 2001). Despite two attempts to get his interpretation of displacement published, he was unsuccessful. Vine and his advisor at Cambridge, Drummond Matthews, published the idea in *Nature* in 1963. Despite this, many still referred to it as the Vine–Matthews–Morley hypothesis.

Their model only gained a warm reception. As data mounted, however, the explanatory/interpretive power of plate tectonics could no longer be discounted. These new data came from the development of the World Wide Synchronized Seismic Network (WWSSN) (Oliver 2001). Implemented in the 1950s as an attempt to discover the testing of nuclear bombs, the WWSSN gave unprecedented seismic data in terms of both quantity and quality. With an accurate delineation of the patterns of earthquake occurrence, the pattern began to emerge suggesting the outlines of tectonic plates. An understanding of the general physics of earthquakes, starting in the early 1900s (Reid 1910), advanced the field of seismology to the point where seismologists were not only able to accurately pinpoint earthquake locations and estimate their depths but also use the record of first movement of a seismic wave to tell the direction of slip along a fault plane. It was this last form of interpretation that verified J. Tuzo Wilson’s (1965) prediction of a new kind of fault found along the mid-ocean ridges—the transform fault—using seismic data (Sykes 1967).

It was this explanatory accuracy, problem-solving capability (Frankel 1987), and retrodictive power that helped lead to final acceptance of the idea of horizontal displacement of the continents (plates) by the vast majority of geologists, fully 60 years after Wegener first proposed it.

The controversy of what actually causes plate motion has not ended, however. There are those, however few, who continue to advocate for an expanding earth (Maxlow 2006; Wilson 2008). The mechanism for the driving of the plates came about once Wilson (1963) proposed shallow stationary "hot spot" plumes to explain the Hawaiian Islands chain. Then it was Morgan (1972) who took Arthur Holmes' (1928) shallow mantle convection model and combined it with Wilson's "hot spot" plume model and then extended them by proposing deep mantle material rising as narrow plumes and then sinking as broad tongues of cooler, denser material in the style of convection cells. Despite some limitations in this theory, it was simple enough (elegant) to garner the attention of many geologists as the explanation for plate motion, eclipsing other multiple working hypotheses (Glen 2005). Although there is consensus that some form of mantle convection is responsible for the lateral motion of the plates, the details of the nature of that convection and the role plates play in the surface expression of earth dynamics are still under much debate (Anderson and Natland 2005; Glen 2005).

It has been the controversies surrounding the development of this grand unifying theory of the earth that have been used by teachers teaching plate tectonics. Sawyer (2010) has used the seafloor data to engage his students in discovering plate boundaries. Paixão et al. (2004) used the controversy between drift and land bridges to engage her participants in discussion and argumentation. Duschl (1987) utilized different explanations for earthquakes to have students compare and contrast them and finally develop arguments for the most appropriate one. Pound (2007) utilized the theory of the hollow earth to engage her students in an activity of critical thinking. Dolphin (2009) utilized many different controversies and alternative models of earth dynamics to facilitate students' understanding of both earth dynamics and the critical evaluation of models. Though the use of these strategies is laudable, none of the experiences were approached in a manner to garner empirical data for gaining understanding of the efficacy of their use.

Another limitation of all of these examples is that though historical models were utilized in the class, it was usually done with the "right answer" in mind. There was no opportunity for the students to create a "wrong" model. In this way, students rationalize their reasoning to fit the conclusion rather than rationalizing data to create their own conclusion (Allchin 2002). A stronger approach in any of these strategies would be to allow students to explore the alternative models *prior to* knowing which model is the best fit. In this way, students utilize multiple working hypotheses, develop critical tests, and must determine the reliability of data as opposed to taking the "right answer" for granted and seeing how the data supports it and missing the scientific process altogether. Later in this chapter, we give an example of a possible approach to instruction using this controversy.

18.6 Biosphere: The Meteorite Impact Theory Explaining the Cretaceous–Paleogene Mass Extinction

On March 4, 2010, the following byline appeared in the popular science Internet site Science Daily:

> The Cretaceous-Tertiary mass extinction, which wiped out the dinosaurs and more than half of species on Earth, was caused by an asteroid colliding with Earth and not massive volcanic activity, according to a comprehensive review of all the available evidence, published in the journal Science. A panel of 41 international experts [. . .] reviewed 20 years' worth of research to determine the cause of the Cretaceous-Tertiary extinction, which happened around 65 million years ago. (http://www.sciencedaily.com/releases/2010/03/100304142242.htm)

This pronouncement was based on an article published by Schulte and colleagues (2010) in one of the most important professional science journals in the world—*Science*. Similar bylines were carried by a broad number of newspapers, websites, and television news agencies around the world. It would seem that, at least to the popular media, the well-known controversy concerning the Cretaceous mass extinction was settled. However, is this true?

To understand this issue better, we briefly return to the 1980 article written by the Berkeley-based team of physicist (and Nobel laureate) L. Alvarez, his son and geologist W. Alvarez, and nuclear chemists F. Asaro and H. Michel (Alvarez et al. 1980) igniting the controversy. Their mass extinction proposal was motivated by their analysis of *unearthly* concentrations of the element iridium, within pencil thick clay layers at three separate locations around the world: (Gubbio) Italy, (Stevns Klint) Denmark, and (Woodside Creek) New Zealand. These layers were formed 65.5 Ma, at the time of the dinosaur extinction at the boundary between the Cretaceous and Paleogene periods (now designated K–Pg, but in the past as K–T). In the earth's crust, iridium is exceedingly rare (measured in parts per billion); however, these exposures showed iridium concentrations of about 30 (Italy), 160 (Denmark), and 20 times (New Zealand), respectively, above the background level at the time of the Cretaceous extinctions.

Based on this evidence the Alvarez group proposed that these anomalous layers were the remnants of a 10-km iridium-rich meteorite that impacted the earth at the end of the Cretaceous. This impact created a global dust cloud that blocked the sun (atmosphere effect) while chilling the planet so that photosynthesis was suppressed causing a collapse in the food chain (biosphere effect). The result was a mass extinction of 75 % of all oceanic animal species and all land animals greater than 20 kg in mass, including all of the (non-avian) dinosaurs.

In the first 14 years of research following this paper, some 2,500 articles and books were published concerning this extinction (Glen 1994a), and this number has easily doubled since then. Like most large-scale, earth science studies, this research brought into play a multidisciplinary and worldwide collaboration of scientists including paleontologists, sedimentologists, (geo)physicists, and (geo)chemists while prompting the development of ingenious experiments, field studies, and new instruments (such as the coincidence spectrometer) to test the varied lines of evidence undergirding this theory. Moreover, although the primary evidence collected to test this theory emanates from the geosphere and biosphere, it has grown exponentially to encompass all of the "spheres" composing the earth. It is truly a global research effort in more ways than one.

In this section we briefly review the evidence underlying this theory while contrasting it with rival mechanisms that have also been suggested for the extinction. This is a perfect HPS controversy that demonstrates the unique features of the earth sciences as a historical and interpretive discipline whose major goal is to reconstruct past phenomena.

From the beginning, the challenge was to locate the estimated 200 km (in diameter) crater, at the K–Pg boundary that was retrodicted by the Alvarez group. As Glen (1994a, p. 12) notes "such a crater, of course would be the smoking gun." An early candidate included the Manson structure in Iowa (Hartung and Anderson 1988), but its geologic composition, size, and radiometric age eventually ruled it out (Hartung and Anderson 1988; Officer and Drake 1989). Thus, the search turned to the Caribbean Basin due to the proposition raised by Bourgeois and colleagues (1988) that at sites near the Brazos River (Texas), an iridium anomaly and the K–Pg boundary usually overlie a sequence of layers that they suggested were deposited by a tsunami that was generated by an impact into the sea. Thus, in the late 1990s, the Chicxulub crater site at the tip of the Yucatan Peninsula in Mexico was suggested as the site of impact (Hildebrand and Penfield 1990; Kring and Boyton 1992); in fact, its discovery was rather serendipitous, dating back to an oil search in 1981, which even at that time, Penfield and Camargo (1981, as cited in Glen (1994a)) suggested as being the remnant of an impact crater.

In the following years, evidence mounted that it indeed was the impact site associated with the extinction. Cores drilled by two separate teams arrived at the same radiometric date of 65.5 Ma (Sharpton et al. 1992; Swisher et al. 1992); moreover, one of the team's (Sharpton) cores indicated an iridium anomaly. Finally, its location has been correlated with the worldwide *ejecta* distribution pattern, related to distance from the Chicxulub crater (Claeys et al. 2002; Smit 1999). Ejecta are materials emitted by the impact including spherules (formed by the rapid cooling of molten material thrown by the impact into the atmosphere), shocked quartz (which are indicative of extremely high impact pressures), and Ni-rich spinels (which are markers for cosmic bodies such as meteorites or asteroids) (Bohor 1990; Montanari et al. 1983).

From a philosophical perspective, the successful uncovering of such physical evidence fits perfectly within our previous discussion of the nature of the earth sciences. This evidence was not manipulated in a set of controlled experiments but was rather gathered by many insightful observations on a set of interrelated signs, exposed during a globally based fieldwork effort. Moreover, such evidence fulfills the all-important scientific function of providing testable, interpretable evidence that could be used to reconstruct a complex and contingent historical event of the past. Many of the previous purely biological hypotheses (such as disease or over-competition) did not leave behind such testable evidence. Moreover, such biological explanations cannot explain the global extinction patterns; consequently, they have been found wanting (Dingus and Rowe 1998). For this reason, many scientists have focused on physical mechanisms including tectonics, sea level, and climatic changes which also favor a gradual extinction pattern.

Especially with the advent of the stratigraphic evidence for impact, some of those opposed to impact coalesced around the hypothesis that massive volcanic eruptions, which occurred between 60 and 68 Ma centered on the Deccan Plateau in west-central India, caused the environmental collapse responsible for the Cretaceous extinctions (Glen 1994a). To satisfy its critics, volcanism must account for the K–Pg boundary evidence that was supposedly left by an impact (Glen 1994a), most notably the anomalous iridium deposits and shocked minerals. In the former case, using actualistic logic, a hallmark of the historical sciences, proponents were able to show that (at least some) modern volcanoes could draw up iridium from the earth's interior at concentration levels matching those found by the Alvarez group (Felitsyn and Vaganov 1988; Koeberl 1989). The latter case, involving shocked quartz, was more difficult to support because although this mineral associated with some volcanic deposits (Officer et al. 1987), its fracture patterns do not match those found associated with the K–Pg boundary (which were the result of high-energy impact). Thus, actualistic reasoning does not seem to support the volcanists' cause. It might be added that the Deccan traps were a nonexplosive type of volcano and so could not be the source of the shocked quartz. So, the volcanists would need to find alternative sites of volcanism to support their arguments, which would concurrently challenge the theory of impact.

As important as the physical geological features are, they are only evidence of impact; ultimately, this is a theory of extinction, which means that the fossil evidence must validate the fact that the impact is the source of the extinction; for even though many scientists accept both the evidence of impact and its timing, there was (and still is) disagreement about the impact as *the only* cause of the extinction. Thus, in analyzing the pattern, we need to divide the discussion into a set of multiple working hypotheses about extinction at the K–Pg boundary to include a gradual pattern (due to a possible combination of physical and biological factors), an "instantaneous" pattern[16] (caused by an impact or volcanism), and a stepwise pattern (possibly caused by multiple impacts). Concurrently, what is also fascinating about this debate is that it divides its supporters along disciplinary lines.

At least at the beginning of the debate, many earth scientists in general objected to impact. Most notable in their opposition were the paleontologists (*the* scientists who are professionally trained to reconstruct fossil life); they specifically objected to impact because the K–Pg boundary was not marked by an abrupt extinction event at the end of the Cretaceous; in other words if impact was the sole cause of extinction, there should have been no major change in the diversity of a group of organisms—such as the dinosaurs—during the Late Cretaceous (Glen 1994c; Ryan et al. 2001; Macleod et al. 1997). Instead, in their view, the fossil record favored a pattern of gradual extinction during the Late Cretaceous.

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[16] Instantaneous in terms of the massive span of geological time.

Such objections to an instantaneous, abrupt pattern are still strong among the paleontological community. In a letter sent to *Science* in response to Schulte and his associates (2010), a team of 23 scientists led by Archibald and his colleagues (2010, p. 973) argued that the review of Schulte et al. (2010) "has not stood up to the countless studies of how vertebrates and other terrestrial and marine organisms fared at the end of the Cretaceous. Patterns of extinction and survival were varied – pointing to multiple causes at this time."

Concurrently, Glen (1994b), drawing upon Pantin (1968), suggested that paleontologists objected to having what is in essence a biological phenomena—extinction—imposed upon them by magisterial authority of the "restricted sciences," i.e., sciences that emphasize the use of a small number of powerful laws in matters of great theoretical significance (such as physics). Such objections were reinforced by L. Alvarez's scathing opinion of paleontologists when he remarked in the *New York Times* (1.19.88) "they're really not very good scientists. They're more like stamp collectors."[17]

Indeed, this was not the first time that such disciplinary conflicts have occurred between physics and earth science. Physicist Lord Kelvin tried to impose a limited geological time scale on Darwinian evolution, and Sir Harold Jeffreys attacked the nascent understanding of continental drift, based on pure physical models, without ever considering the validity of the geological evidence (Dodick and Orion 2003). In these historical cases the magisters of physics ignored the methodological uniqueness of historical sciences; so too the paleontologists argued that L. Alvarez was also wrong in his interpretation. Partly trained in biology, paleontologists understand that like other historical events extinction is a complex, contingent phenomenon that cannot always be reduced to a single cause as Archibald and his colleagues (2010) intimated in their recent reply to Schulte his associates (2010).

Such disciplinary battles have even extended within the earth sciences. Geochemistry, planetary geology, and other more physically oriented branches of the earth sciences were more inclined at the beginning of this debate toward accepting impact (Glen 1994b). Even today, such divisions exist as Archibald and colleagues (2010, p. 973) criticized Schulte's (mostly) physical geological team because it did not include researchers "in the field of terrestrial vertebrates…as well as freshwater vertebrates and invertebrates." It might be added, however, that today most paleontologists accept the idea of impact as one of the extinction factors (along with marine regression, volcanic activity, and changes in climatic patterns), so the physical geologists and paleontologists have drawn somewhat closer together.

In the last half of the 1980s, as more scientists look at the K–Pg boundary layer, a third extinction pattern was suggested—stepwise mass extinction—in which

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[17] This critique of paleontology has antecedents in Ernst Rutherford's famous quote about science in general: "All science is either physics or stamp collecting." In his book, *Wonderful Life*, Gould (1989) makes a strong argument for the special nature of the historical sciences, such as paleontology, and their methods, as well the general value of epistemological diversity in the sciences. This argument eloquently recapitulates many of the points raised in our chapter in the section dealing with the nature of the earth sciences.

different kinds of organisms disappear within different layers before the end of the Cretaceous and the layer containing the iridium (Mount et al. 1986; Keller 1989). Correlated with this finding is the fact that in some localities, iridium is not restricted to the K–Pg boundary clay but appears to diminish gradually in concentration as one moves up or down from this layer (also termed "smeared anomalies"). Such evidence points to the possibility that multiple impacts were responsible for the extinction (Dingus and Rowe 1998). At the same time some of the volcanists have seized upon such stepwise patterns as supporting their claim, as it fits the major pulses of volcanic activity and associated environmental havoc resulting from periodic eruptions, which they claim happened in the Late Cretaceous.

Surprisingly, the earth science community also objected to impact because according to historian of science Glen (1994a) and paleontologist Gould (Glen 1994c), instantaneous global effects violate the understanding of one of geology's most important principles—uniformitarianism. Uniformitarianism has had many different interpretations over its history (Oldroyd 1996), but it would appear that the definition that many earth scientists adopted was the restrictive definition of Lyell (1880–1883), which assumed that in geology "no causes whatever have . . . ever acted but those now acting, and that they never acted with different degrees of energy from which they now exert" (Lyell 1881, vol. 2, p. 234). In other words actual causes were wholly adequate to explain the geological past not only in kind but also in degree (Rudwick 1998). Lyell based his uniformitarianism definition on Newton's use of the philosophical principle of vera causa in which only those processes operating today would be accepted as geological causes (Laudan 1987).

Lyell's adoption of Newton's vera causa was his philosophical response to geologists who invoked catastrophes as earth shaping forces. Lyell disapproved of catastrophes because they implied that geology relied upon unknown causes, which violated the principle of simplicity (i.e., the best scientific explanations are those that consist of the fewest assumptions). Lyell believed that the a priori application of uniformity (based on vera causa) was necessary, if geology, like physics, was to be considered a valid, logically based science (Baker 1998, 2000). However, the adoption of such restrictive principles is short sighted because it does not consider geology's unique defining characteristics, its historical interpretive nature, and indeed, during Lyell's time his definition of uniformitarianism was largely rejected, yet in the twentieth century, it influenced the thinking of many earth scientists (Dodick and Orion 2003). In simple terms, such scientists were trying to be more like physicists than the physicists in their application of this defining principle.

Today, the situation has changed. With mounting evidence, most earth scientists do accept the reality of an impact 65.5 Ma. However, the debate continues about whether it is the sole cause of the mass extinction or just one of its contributing factors. Thus, paleontologists continue their examination of the K–Pg boundary to more accurately delineate the extinction patterns on the biosphere. Similarly, sedimentologists, (geo)chemists, and (geo)physicists continue their mapping of the K–Pg layer to better understand its geology and the devastation an impact would have imparted upon the Cretaceous geosphere, hydrosphere, and atmosphere.

For those interested in earth science education, the debate surrounding the K–Pg extinctions is a perfect historical controversy that summarizes many of the most important features of the nature of the earth sciences as a unique branch of science. Concurrently, it shows how the human factor of philosophical and disciplinary prejudices shapes the actors in a debate, sometimes in spite of what the "objective" evidence says. Thus, this controversy deserves a place in any well-designed earth science curriculum.

18.7 Hydrosphere: Ocean and Atmosphere Coupling

The section that follows will discuss aspects of a coupled ocean/atmosphere phenomenon in the Pacific Ocean with dramatic effects on long-term weather all over the world. At first glance, it seems that when talking about El Niño and the Southern Oscillation (ENSO), one might not think of it as a controversial issue at all, but even in the late 1990s, many scientists in the fields of weather, climate, and oceanography still considered ENSO researchers as "renegades" (Cox 2002) when Ants Leetmaa successfully predicted and publically announced a major El Niño event to occur that year, along with predictions of severe long-term weather. The fact is there were many controversial issues needing resolution before ENSO could gain consensus as an explanation for aberrant, long-term global weather. It took almost 100 years of investigation to gain full consensus, including with the general population, from scientists' first awareness of a possible connection between a warm current off the west coast of South America and unusually mild or wet winters in parts of North America and Europe and drought conditions in Africa, India, and Australia.

As we have tried to demonstrate with each of the controversies highlighted within this chapter, the phenomenon of ENSO is one of global scale and has influence on all of the earth systems. Though El Niño is the name Peruvian and Ecuadorian natives gave to the occurrence of a warmer than normal current along the eastern margin of the Pacific Ocean basin, ENSO identifies a phenomenon that actually results from the *interaction* of the ocean and the atmosphere to create conditions that have a profound impact on the long-term weather and biota around the globe. To give an example of the scope of impact, Glantz (1996) listed these effects of the 1982–1983 El Niño event. There were droughts in Africa, India, and Central and parts of South America, to which 400 deaths and almost $7 billion (USD) in damages were attributed. At the same time, flooding in parts of Western Europe, South America, the USA, and Cuba were responsible for about 300 deaths, 600,000 people being displaced, and $5.5 billion in damages accumulating. Severe storms and tropical cyclones battered many of the islands in the Pacific from Hawaii to Polynesia, as well as large portions of the USA. Effects were also detrimental to the East Pacific fishing industry and to the nesting sites for 10s of millions of birds on Eastern Pacific Islands and the west coast of South America. Likewise, Philander (2004) noted that over 20,000 deaths; over 100,000,000 physically affected, including 5,000,000 displaced; and $33 billion in damages resulted from the 1997–1998 El Niño event. The phenomenon identified as ENSO is global; its impact, significant.

The story of ENSO is also one demonstrating the convergence of studies. In this case, studies focused on ocean circulation and on atmospheric circulation (i.e., it takes into account the hydro- and atmospheres). It was this dichotomy, atmospheric science versus oceanography, which played a role in the controversy, as our understanding of how the air and ocean interact to influence long-term global weather patterns. This included the theoretical pitting of the meteorologists (mainly American), who, as empiricists, utilized patterns observed in synoptic weather maps to form short-term weather predictions, against the forecasters (mainly from the European Bergen School of Meteorology) who utilized the physics of the atmosphere and computed weather forecasts, by hand at first but then by computer (Cox 2002). There were the philosophical differences in looking at the phenomenon. It made a difference whether one saw El Niño as a departure from the normal conditions or whether they saw it as a uniform cycle perturbed by outside, random conditions (Philander 2004). There was also the clash of personalities (Cushman 2004a). Jerome Namias looked to the north at the polar front and an atmospheric oscillation known as the Rossby wave to be the control of long-term weather around the world, while Jacob Bjerknes looked to the tropical pacific and the Southern Oscillation, first discovered by Gilbert Walker, as the main impetus for long-term weather variations.

A severe drought in India from 1877 to 1899 and ensuing famine caused the British government to send Gilbert Walker to India, in 1904, to become the head meteorologist and attempt to better forecast the monsoons than then current meteorologist, Sir John Eliot. Eliot's forecasts were descriptions upwards to 40 pages long … and mostly incorrect. Walker was an unlikely candidate for this position as he was trained as a statistician. However, he set to work recording weather conditions around the world. He noted some correlations among distant locations on earth. One of these was a "swaying" of the atmosphere in the tropics of the Pacific Ocean. When there was high pressure in the west, there was low pressure in the east. When it was high in the east, it was low in the west. He called this swaying the *Southern Oscillation*. He also found that observations of the weather in distant parts of the world correlated highly with this oscillating air over the Pacific Ocean. However, his findings did not impress many of the meteorologists of the time because they were strictly mathematical and therefore only descriptive. In other words, because Walker postulated only correlations and no explanation for the correlations, it made other meteorologists very skeptical of the findings. From the point of view of the meteorologists, Walker was not doing science in the conventional "make a hypothesis and then test it" way (Cox 2002). In essence, however, Walker *was* doing science, in an historic and interpretive sense. Paralleling what we described above, he looked at complex and preexisting entities to discern patterns and interpret them.

At approximately the same time, on the west coast of South America, a peculiar periodic warm current, years earlier named El Niño by Peruvian fishermen, became the focus of scientific inquiry (Cushman 2004b). *El Niño*, translated into English, means *little boy*, but when capitalized, it intimates *the Christ child*, or *Jesus Christ*. They gave this name because of the phenomenon's repeated occurrence around Christmastime. They identified this phenomenon because it brought with it disruptions in normal rainfall patterns as well as behavioral (including nesting and reproductive) patterns in fish and birds along the west coast of South America. Most considered El Niño to be a local phenomenon affecting only portions of South America and therefore did not warrant much attention. The phenomenon became very important to the USA after a strong El Niño event during 1925–1926 caused major disruptions in the US fishing industry in the Pacific. As Cushman (2004b) described in his book, the importance of business, colonialism, and national security has motivated intense study to modern times, into the connection between the ocean and the weather.

Robert Murphy, an ornithologist from the USA, noted the effects on the bird populations he was studying and proposed a connection between Walker's Southern Oscillation and the El Niño event he was experiencing. However, there was a great deal of doubt concerning the reliability of the data Murphy was using, as well as concerns about the connection between oceanic and atmospheric phenomena (Cushman 2004b). Then, through the 1930s and 1940s, interest in El Niño waned. Up until that time, US agricultural interests were wrapped up in Peru because the Peruvians were the world's largest producers of bird guano, much of which was exported to the USA as fertilizer for the growing agricultural industry. Bird nesting habits and therefore guano production were very much influenced by El Niño, but that became a nonissue with the development of man-made fertilizers (Glantz 1996). As the economic importance of guano production waned, so did the interest in studying El Niño.

It was not until post-WWII and the Cold War era that physical properties of the ocean again became of national interest and new studies began. The International Geophysical Year, 1957–1958, coincided with this renewed interest. Many countries began recording data with better equipment and with greater rigor than previously. National security and national self-interest through the US fishing industry precipitated a renewed interest in ocean and atmosphere dynamics. Jacob Bjerknes, son of famous meteorologist, Vilhelm Bjerknes, and creator of the cyclone model of mid-latitude weather, turned his attention to El Niño. He discerned a connection between the Southern Oscillation, what he identified as *Walker Circulation*, and the periodic warming of the tropical Pacific Ocean, known as El Niño. Bjerknes and others such as Jerome Namias, who earlier had helped model upper atmosphere oscillations known as the Rossby wave, echoed claims already made of the connection between the atmosphere and ocean and their affect on weather in distant parts of the world. Such cross-disciplinary studies—oceanography and meteorology—were conceptually new and as yet quite suspect from other scientists. Where Bjerknes looked to the Walker circulation in the tropical Pacific for an explanation of global, long-term weather, Namais looked instead to the mid-latitude polar front as the engine driving such phenomena (Cushman 2004b). The military became interested in developing new buoy technologies motivated by its need for defense against Russian nuclear submarines. As a side note, it was this same fervent interest in the ocean by the military that generated the JOIDES (Joint Institutions for Deep Earth Sampling) expeditions that were so instrumental in collecting the seafloor data later used in support of the theory of plate tectonics. With the international efforts to collect data, Bjerknes had the resources to connect El Niño with the Walker circulation (Southern Oscillation). The study of ENSO began at that point.

The mechanism discerned by Bjerknes to explain his observations was that in the Pacific, along the equatorial region, winds generally blow from the east across the basin to the west. This pushed the warm water to the west and allowed a rise of the thermocline, the thin layer of water separating warm, well-mixed upper-level water from the colder, less-mixed water below. This brought the cold water to the surface making the west coast of South America cool and dry. An El Niño event was identified when the easterlies were not so strong and warm water resided in the eastern parts of the Pacific Ocean basin. This warm water interrupted fish migrations. It was also responsible for warmer, moister regional weather which interrupted bird nesting behaviors. It also caused more rain along the western coasts of North and South America and affected long-term weather all through Africa, North America, and Europe, as noted above. Here again, as we have recounted in each of these sections, this phenomenon spans its impact into many realms of study from the physics of energy exchange between the air and the sea to the effects on life on earth. In essence, rather than being a derivative science, the geosciences are more a place for the practical application of understandings from the other disciplines.

The scientific community was still divided, however. There was skepticism in being able to mathematically model the weather. There was skepticism in the utility of cross-disciplinary investigation. They saw El Niño scientists as renegades (Cox 2002). There was skepticism that a local fluctuation in ocean surface temperature could explain worldwide weather. The idea gained traction, as the number of published articles related to El Niño doubled every five years from 1980 to 2005 (Philander 2004). What the public heard of El Niño and its effects through the 1980s and 1990s resulted in its conflation with other atmospheric hazards making the news at that time, namely, the hole in the ozone layer over Antarctica and threats of global warming. Many considered reports of El Niño as just another liberal, big government orchestration (Cox 2002), very much like that continuing to surround the issue of global climate change today.

It was not until 1997, when Ants Leetmaa, then director of the National Climate Prediction Center, declared on national news that he expected a very significant El Niño event. For the previous decade or so, the National Climate Prediction Center had been participating in and receiving data from the Tropical Ocean Global Atmosphere (TOGA) program. Leetmaa and others receiving these data noted a warming of the waters at a far faster pace than had been observed before. Guided by computer simulations, Leetmaa laid out a number of predictions of anomalous long-term weather conditions contingent on this warming, including heavy rains in Southern California and the rest of the Southern USA and a warmer than usual winter in the northeast of the country. He also talked of a more quiescent than normal hurricane season. Reception of Leetmaa's warnings was cool. Many thought that Leetmaa had overstepped the types of predictions ENSO scientists were able to make. El Niño became somewhat of a household name the following spring when these predictions came to pass.

In this sense, the concept of ENSO had an advantage in its explanatory power as well as its relatively short-term predictive capabilities over the other controversies noted in this chapter. Various computer models, an example of multiple working hypotheses, used initial conditions and projected outcomes into the future: an interpretation of how nature *will be* as opposed to the plate tectonics controversy or the dinosaur extinction controversy where events had already taken place and scientists were left to interpret the results of *past actions*. Similarly, there are many investigations looking into how to utilize effects of El Niño to interpret the extent of past El Niño events.[18] Leetmaa reported his predictions and everyone could be around to witness whether they came to pass or not. It was not an experiment in the sense that variables were controlled, but it had the feeling of an experiment because predictions were made and it was just a matter of waiting them out. This type of "natural experiment" is very characteristic of the historic sciences, like the earth sciences. In this case, the ENSO phenomenon happens on a scale of time that makes it possible to make predictions and see them borne out over several months. And the fact that the predictions were fulfilled gave strength to the models and gave rise to a general consensus within the scientific community as well as the general public concerning the validity of ENSO—the interaction between ocean and atmosphere—as a world weather controller. It also provided evidence supporting the use of computers to predict long-term weather.

18.8 Global Warming: A True Controversy?

Depending on the background of the reader, the title of this section should give pause. If we were to survey climate scientists, then the vast majority would agree with the primary conclusions of the Intergovernmental Panel on Climate Change (IPCC)[19] (IPCC 2007) which states that anthropogenic greenhouse gases have been responsible for most of the "unequivocal" warming of the earth's average global temperature over the second half of the twentieth century. In fact, in their extensive study of (1,372) climate researchers and their publications, Anderegg, Prall, Harold, and Schneider have shown that

> (i) 97–98 % of all of the climate researchers most actively publishing in the field [surveyed in their research] support the conclusions of the IPCC and (ii) the relative climate expertise and scientific prominence of the researchers unconvinced by anthropogenic climate change (**ACC**) are substantially below that of the convinced researchers. (Anderegg et al. 2010, p. 1207)

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[18] See, for instance, Galbraith et al. (2011), Khider et al. (2011), Nippert et al. (2010), and Romans (2008).

[19] Created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, IPCC's purpose is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (Oreskes 2004).

Similar results were obtained by Doran and Zimmerman (2009) in their web survey of over 3,000 earth scientists, as well Oreskes's (2004) analysis of (928) abstracts dealing with climate change, published in refereed journals from 1993 to 2003. Finally, Powell (2011) on the *Skeptical Science* Internet site surveyed 118 of the best-known ACC skeptics. He found that 70 % of them have no (peer-reviewed) scientific publications that deny or cast substantial doubt on ACC. Moreover, none of their papers offers a "killer argument" falsifying human-caused global warming. The best they can do is claim that the measurement sensitivity of ACC is low, which they have been unable to substantiate and which much evidence contradicts (http://www.skepticalscience.com/Powell-projectPart2.html). So it would seem that at least among the majority of professional scientists who are most active in climate research, ACC is accepted as a (worrisome) trend that requires immediate response from nations around the world to ameliorate.

However, among the US public, the story is very different. In a recent Gallup poll, 51 % of its citizens expressed concern over ACC in 2011, compared to 65 % in 2007. Moreover, 52 % of the 2011 survey believed that the increase in the earth's temperature was due to pollution from human activities as opposed to 43 % who believed that it was due to natural changes in the environment. Just four years previously these figures stood at 61 % and 35 %, respectively (http://www.gallup.com/poll/146606/concerns-global-warming-stable-lower-levels). Clearly, much of the US public does not agree with the implications of much of the peer-reviewed research. Although not as severe, skepticism about ACC has also increased in the European Union, Canada, Australia, and New Zealand, based on surveys conducted in the last three years (Ratter et al. 2012). Thus, in the case of ACC, the public controversy is at odds with the much higher acceptance that this phenomenon has received among the majority of climate scientists, as well as their scientific colleagues within the wider earth science community.

One result of this controversy is that it impacts how students understand the workings of the atmosphere. In fact, ACC is a special subject because students face two challenges to their learning about it. First, like all other earth science topics discussed in this chapter, ACC is a complex scientific problem that is studied by a multidisciplinary, global team of climate scientists, oceanographers, atmospheric chemists, and geologists. Even in their early years at university, students do not usually have the broad background to understand this problem; adding to this problem is that they also hold large numbers of misconceptions about this and other atmospheric issues.[20]

Second, in order to understand ACC, students (like the general public) must overcome misinformation perpetuated by a smaller number of vocal, skeptical politicians and experts that are the source of the controversy (Theisen 2011). Relative to the much larger community of experts who have gathered strong evidence for ACC, the skeptics have a broad platform in the public media; this is due to the balance that

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[20] See, for instance, Gautier et al. (2006), Jeffries et al. (2001), Shepardson et al. (2011), and Theisen (2011).

the media gives to this issue—a balance which in fact diverges from the much greater acceptance this issue receives from professional scientists (Boykoff and Boykoff 2004). Indeed, in her study of students at the University of Vermont, Dupigny-Giroux (2010) found that most undergraduates cited some form of media as their primary information about climate, which in turn reinforces their misconception that a (balanced) controversy exists.

In this regard, ACC which is played out in the public eye differs from the other three controversies, presented in this chapter, which are largely debated among scientists and have had much less impact on the public. This controversy is less politically contrived than the false "controversy" that religious forces have presented in order to falsify evolution. However, as we will see, the roots of the ACC controversy also have political overtones, which are partly derived from the scientific background and motivations of some of its opponents, as well as the general economic situation which influences the publics' attitudes.

Thus, the question that we need to ask is as follows: If much of the scientific establishment supports ACC, how does such skepticism thrive? To answer this question we will (briefly) examine the history of the ACC idea. Concurrently, we will show that the ACC problem encompasses many of the unique features of the earth sciences. We believe that it is important for students to understand these historical and philosophical features of the ACC idea because it helps to explain the background behind the scientific and even political opposition.

The earth maintains a habitable temperature because of the natural greenhouse effect occurring in its atmosphere. Various atmospheric gases contribute to the greenhouse effect, whose impact in clear skies is 60 % from water vapor, 25 % from carbon dioxide, 8 % from ozone, and the rest from trace gases including methane and nitrous oxide (Karl and Trenberth 2003). Clouds also add to this greenhouse effect. On average, the energy from the sun received at the top of the earth's atmosphere amounts to 175 petawatts (PW = a quadrillion watts), of which 31 % is reflected by clouds and from the surface. The rest (120 PW) is absorbed by the atmosphere, land, or ocean and ultimately emitted back to space as infrared radiation (Karl and Trenberth 2003).

Since the early twentieth century, the average temperature of the earth's surface has increased about 0.8 °C, with about two-thirds of that increase occurring since 1980 (NRC 2011). Such global warming is caused by increasing concentrations of greenhouse gases produced by human activities such as deforestation and the burning of fossil fuels (NRC 2011). As such concentrations rise, they act to increase the opacity of the atmosphere to infrared radiation, trapping it in the atmosphere and raising the temperature of the planet.

The idea of ACC is not recent; indeed, the idea that changes in atmospheric greenhouse gas concentrations can and do cause significant climate changes was proposed qualitatively in 1864 by renowned physicist John Tyndall, when he discovered carbon dioxide's opacity to IR radiation (Sherwood 2011). In 1896 the future Nobel chemistry laureate Svante Arrhenius quantitatively predicted that such warming would be caused by coal burning; the prediction was tested and promoted by steam engineer Guy Callendar in the late 1930s (Sherwood 2011).

In the 1950s, the scientific debate focused on whether or not greenhouse gases were accumulating in the atmosphere and, if so, what affect this was having on global temperatures. Against the background of this debate, chemist David Keeling, from the Scripps Institute of Oceanography, sought to find out; in 1957, he set up an array of newly developed gas analyzers on Hawaii's Mauna Loa volcano to measure atmospheric levels of carbon dioxide. Keeling discovered two trends: first, he measured the average monthly value at 315 p.p.m (p.p.m. = parts per million). Keeling saw the values drop from May to September and then rise again into the next year. This cycle continued with decreases in the summer when plants soak up carbon dioxide and grow and increases in autumn and winter when plants are less biologically active (Smol 2012).

The second trend found by Keeling was that global carbon dioxide levels were rising annually from various human activities, creating a rising trend on the graph he constructed. Measurements that continue until the present demonstrate that atmospheric carbon dioxide concentration had risen to 394 p.p.m by June 2011. Moreover, the current carbon dioxide level far exceeds its natural fluctuation (180–300 p.p.m.) over the past 800,000 years. Scientists reconstructed this historical range by studying the planet's natural archives, represented by natural traces found in tree rings, the sediments of lakes and oceans, and ice cores (Smol 2012). Such proxy records combined with measurements of global temperatures today have shown that the world has warmed throughout the twentieth century. Models of such warming into the future suggest and predict that the earth will continue to warm into the future.

Climate scientist Steven Sherwood (2011) framed the historical development of the ACC idea by comparing it to some of the major paradigmatic shifts affecting physics. For example, Copernicus' published his model of the heliocentric universe in 1543. However, it was not until Kepler's calculations of 1609 (Gingerich 2011) and Galileo's observations in 1610 that provided the critical evidence to convert the top astronomers to the Copernican view. Nonetheless, acceptance among most scientists did not occur until the late seventeenth century, while the public at large remained opposed until the eighteenth century (Kuhn 1957). A similar pattern was seen in the fight for acceptance of Einstein's theory of general relativity (Sherwood 2011).

In the case of the heliocentric universe, a large source of public criticism was religion. As Gould (1987) and Freud before him noted, the invention of a heliocentric universe is one of seminal scientific discoveries as it displaced humans from the center of the universe, breaking their cosmological closeness to God. Such a view threatened the political power base of the Church which saw itself as the guardian of the human connection to God, and it is well recorded about the pressures that the Church brought to bear on scientists who supported Copernicus. In the case of Einstein, religious and political factors also affected the public debate against him and his theories, as anti-Semitic jibes and accusations of being a communist were thrown in his direction (Sherwood 2011).

In the case of global warming, politics is also a strong motivator of public skepticism. Gauchat (2012) has analyzed trends in public science in the USA from 1974 to 2010. He found that conservatives began this period with the highest trust in science, relative to liberals and moderates, and ended the period with the lowest; with regards to ACC, specifically, a decreasing number of conservatives doubt that it is occurring. Complicating the political situation are economic factors. In evaluating public opinion data from the USA, Scruggs and Bengali (2012) suggested that the decrease in belief about global climate change is likely driven by economic insecurity connected to the recent recession. A similar analysis of opinions from the European Union supports an economic explanation for changing public opinion.

However, such public skepticism does not explain the scientific skepticism for global warming. We have already seen that the peer-reviewed data overwhelmingly supports ACC and that the scientific skeptics largely do not come from the forefront of climate research. Therefore, we ask: why does such scientific skepticism survive and even thrive?

Sherwood (2011, p. 42) has argued that it is the very nature of global warming, as a scientific problem, that has created the skepticism among some scientists. He suggests that the heliocentric universe, general relativity, and global warming have all been scientifically opposed because of the "absence of a smoking gun or a bench top experiment that could prove any of them unambiguously." Moreover, he notes that what global warming shares with the other theories is: "its origins in the worked-out consequences of evident physical principles rather than direct observation." Such "bottom-up deduction is valued by physics perhaps more than by any other science," and many of the leading climate scientists were trained as physicists. Finally, he adds that global warming is based on "physical reasoning… rather than on extrapolating observed patterns of past behavior."

We agree with Sherwood's (2011) assessment that it is the misunderstanding of the scientific nature of the global warming problem that is one of the sources of its opposition. However, we do not think that this is connected to it being a strictly physics-based problem. In fact, the characteristics that Sherwood uses to define this problem also fit well within the structure of historical sciences (such as the earth sciences) that we mentioned earlier in this chapter. Most of the problems that the earth sciences tackle do not lend themselves to benchtop, controlled experiments nor direct observations, due to these sciences' massive scales, both in terms of space and time, as well as the large number of interacting variables that are impossible to replicate and control in the laboratory. Moreover, although some climate scientists certainly create multiple mathematical models, what we consider to be multiple working hypotheses, in order to predict the magnitude of future trends in global warming, others are using, as we have seen, evidence from the past such as ice cores and tree rings to reconstruct the past atmosphere. So there is a strong element of "history" in this research as well.

These arguments, concerning the nature of different sciences, are inadvertently supported by Oreskes and Conway (2010), in their book *Merchants of Doubt*. A main theme of this book is that a handful of politically conservative physicists in the USA, with strong ties to both industry and conservative think tanks (such as the George C. Marshall Institute), have challenged the scientific consensus on issues such as the dangers of smoking, the effects of acid rain, and the existence of ACC.

The authors charge that this has resulted in deliberate obfuscation of these issues which in turn has influenced public opinion and governmental policy.

Oreskes and Conway's (2010) main argument is about the deleterious effects of politically connected, powerful scientists on the government's environmental and health policy. However, it is interesting to note that they specifically identify Bill Nierenberg, Fred Seitz, and Fred Singer as the three physicists who were most prominent in leading the battle against ACC; Nierenberg and Seitz were part of the Manhattan (atomic bomb) project, whereas Singer developed earth observation satellites. In simple terms all three scientists came from branches of physics that more closely rely upon experimental, reductionist methods. Possibly, it is their scientific background which creates prejudice against the multidisciplinary, historical, and interpretive methods of global climate research. This, combined with their political histories as past cold warriors, who also represent conservative business and political interests, creates a synergistic effect to their skepticism against ACC.

There is no doubt that the political power and media connections of this much smaller group of scientific skeptics are strong. In the science education world, its influence has created confusion among (earth science) students. However, if Sherwood (2011) is correct about its historical progression, the science will eventually be accepted by both scientists and the public. The question that remains of course is how future generations will deal with our lack of action today.

18.9 Designing Curricula Utilizing HPS and the Controversies: Plate Tectonics as an Exemplar

We have given an outline of the development of scientific understanding of four different phenomena through the lens of the controversies surrounding each understanding. In this section, we would like to offer some possible direction for designing instruction that utilizes a modern theory of learning as well as the history and controversies surrounding the phenomena to promote, in students, useful understanding of content as well as aspects of the nature of science.

Researchers have discerned a pattern of learning encompassing the iterative process of developing a mental model of a phenomenon, deriving predictions from the model, testing the predictions, and finally, amending the original model to agree with the new data (Nersessian 2008) or generating, evaluating, and modifying the model (Clement 2009). By starting with this structure, an instructor can utilize historic models and data to encourage students to create their own models of a phenomenon, make predictions from the models, look at the historic data, and determine the usefulness of their models to make predictions. The instructor can also encourage model co-construction (Khan 2008), model evolution (Núñez-Oviedo et al. 2008), and model competition, disconfirmation, and accretion (Núñez-Oviedo and Clement 2008) through the use of personal models, class-generated models, and historic models.

We would start with fundamental concepts or big ideas. They can be garnered from the core disciplinary concepts of the NGSS (Achieve 2012) or one of the big ideas found in the Earth Science Literacy Principles (Earth Science Literacy Initiative 2010). Or, the instructor can discern his/her own fundamental concepts by using the discourse tools found at http://tools4teachingscience.org. For this example, we will use the concept of earth dynamics as it pertains to the theory of plate tectonics. We envision this fundamental concept or primary concept as an amalgam of six secondary concepts (volcanology, seismicity, oceans and continents, geomagnetism, the earth's internal structure, and radioactivity). Of course these are not the only secondary concepts that one could use, nor do they have to be these specific concepts. Finally, we discerned about three or four tertiary concepts from each secondary concept. Tertiary concepts are the learning objectives of individual lessons. For instance, for the secondary concept, "seismicity," possible tertiary concepts are "earthquakes," "elastic rebound theory," and "global seismicity patterns." These tertiary concepts are the foci or instruction using the original documents, data, historical narratives, and inquiry activities.

A brief outline of a possible approach to incorporating HPS and the content material within the structure of model-based learning follows. We would have students read two eyewitness accounts of the 1906 San Francisco earthquake: one by Jack London (1906) and William James (1911). As a follow-up to the readings, we would have students develop an initial mental model of an earthquake, based on their prior understanding and the content of the readings, by asking them what an earthquake is and what causes it. Model competition, model disconfirmation, and model evolution then take place through presentation and class discussion of mental models.

Following student work on their mental models, we would have them read excerpts of H. F. Reid's (1910) report and description of elastic rebound theory. Discussions about Reid's earlier work studying glaciers and how the behavior of glacial ice may have been his model for the behavior of rock could illuminate for students how prior experience can influence thinking about unrelated problems. Subsequent to this discussion, students would break into groups and participate in an activity utilizing the earthquake machine http://www.iris.edu/hq/resource/redefining_an_earthquake_v12, where they can gain an understanding of the nature of the storage and release of elastic energy, as well as the use, strengths, and limitations of models. With the understanding of an earthquake being a release of elastic energy built up in deformed rocks, students can utilize such computer visualizations as the US array record of such earthquake events as the 2011 event in Japan (http://www.youtube.com/watch?v=Kbc0ERoCD7s) and data storage sites such as Rapid Earthquake Viewer (http://rev.seis.sc.edu/) where they can develop a sense of energy released by an earthquake in the form of waves that travel through the earth and be observed by sensitive equipment.

Next, we would ask students about possible causes of earthquakes. Once they have developed their own models, we would have them read excerpts from or summaries of multiple historic models of earth dynamics. These would include Aristotle's porous earth (Şengör 2003), contracting earth (Malaise 1972; Schuchert 1932), continental displacement (Du Toit 1937; Wegener and Skerl 1924), and expanding earth (Carey 1976; Jordan 1971). Students would then, in small groups or whole class discussion, identify the strengths and limitations of the historic models alongside current student models for the cause of earthquakes. Again, we would have students be aware that models of earth dynamics were often dependent on the region used for delineating the model. Aristotle developed the porous earth model within the karstic topography of the Mediterranean. Seuss and Dana developed the contracting earth models during their work in the folded mountains of the Alps and the Appalachians, respectively. Wegener's experience with icebergs may have influenced his model for drifting continents through ocean crust.

Students should also be made aware of the controversies surrounding these models. One issue had to do with the idea that earth dynamics behaved mainly in a vertical direction (porous model and contraction model) versus deformation resulting from horizontal motion (continental displacement and expanding earth models). Other issues dealt mainly with issues surrounding the controversy between drift and permanence theories. Wegener and Du Toit pointed out the difficulties of contraction with the understanding of isostasy and that it could not explain fossil, geologic, and geographic similarities among widely separated continents. The "fixists," on the other hand, accused those in favor of displacement of not having an appropriate mechanism for moving continents, of deciding on their explanation and going in search of evidence to prove the explanation, and of not adhering to the philosophy of uniformitarianism.

We would ask students to use these models, in addition to student- or class-generated models, as multiple working hypotheses. They should determine the implications of each model, and then think of places they would look to find more data to test them. When someone directs attention to the ocean, some readings concerning the history of ocean exploration (Höhler 2003), Marie Tharp (Lawrence 2002, pp. 181–188) and Tharp's discovery of the mid-Atlantic ridge and rift system (Heezen et al. 1959), help students to understand the historical development of physical oceanography. Discussions of continued reticence for accepting drift, as well as the influence of World War II and breaking telephone cables as incentive for exploring the seafloor continue to develop the social and economic factors influencing the direction of scientific investigation. Then students can look at various kinds of seafloor data such as utilized in the "Discovering Plate Boundaries" activity (Sawyer 2010). Here students will look for relationships among patterns of sediment thickness, ocean crust age, bathymetry, and seismic and volcanic patterns. Using these data, students can test their models and the historical models to determine how they hold up to the data.

Then we would introduce students to explorations into paleomagnetic studies (polar wandering and magnetic reversals) and how it tied all the data together (Glen 1982) for those such as Hess (1962) and Vine and Matthews (1963). Finally, discussions into mantle convection, Wilson's prediction of transform faults (Wilson 1965), and the World Wide Synchronized Seismic Network should give students enough information to develop a model of earth dynamics very similar to the current scientific model. A key point throughout the entire instructional series is that the students are allowed to *develop their own model* of earth dynamics as opposed to rationalizing data and identifying "wrong" models because they already "know" the right answer. The questions we would ask are open for students to foster inquiry into the data and model building/testing/amending from the data. In this way, students experience "science in the making" (Conant 1947, p. 13) as opposed to finished science.

18.10 Conclusion

We have accomplished a few goals within this chapter. The first was to highlight the historical and interpretive nature of the geosciences as distinct from the experimental nature of physics and chemistry. All of the models developed by investigators have the purpose of explaining observations of effects of events that have already happened. In some cases, these explanations allow us to peer in the future, but not in any kind of controlled way. Phenomena (shifting plates, long-term weather, meteorite impacts) will proceed as they will and we can only witness them and measure them against our predictions. Second, we demonstrated the global nature of phenomena being investigated within the geosciences. Each of these topics has or has had fundamental effects within all spheres of earth systems and has had impacts that extend around the world. This is not to say the earth scientists do not study strictly local phenomena, but even these local phenomena can be traced back to global causes.

Third, was to demonstrate that it was often the convergence of multiple disciplines involved in independent investigations that led to the eventual development of reliable explanatory models of the phenomena in question. Within this framework, we also found that the interdisciplinary nature of many of the investigations gave rise to the controversies in the first place. This was often the case because the different disciplines operated under different philosophical constraints or followed different rules and politics. Especially relevant were issues surrounding the nature of nature. For instance, do phenomena happen based in uniformity (cyclic) or catastrophe (unidirectional)? In the case of continental displacement, the interpretation by some that it did not conform to uniformity as defined at the time may have delayed its acceptance. We also cited uniformity as an issue to accepting the bolide theory for explaining the extinction of the dinosaurs. Another example of a difference in philosophical stances toward nature was L. Alvarez's interpretation of the extinction event at the end of the Cretaceous. Alvarez, an experimental physicist, believed that impact was the cause of all of the mass extinction events in earth history. According to Gould (Glen 1994c) he sought a universal mechanism for mass extinctions. This approach differs from the historical sciences, which interpret natural phenomena, such as extinction, which are seen as complex and contingent, and dependent on a large series of often interacting factors. In other words, just because a meteorite impact caused a single mass extinction, it does not necessarily mean that all mass extinctions were caused by impact. History has shown that Alvarez's hypothesis of a universal mechanism was not correct.

Fourth, we showed the relationship between scientific advancement and technological advancement. Oftentimes, it was technological advancements responsible for gathering more accurate data and a refinement of methods that increased its reliability. For plate tectonics, it was more sensitive magnetometers, the advancements in seismic recording with the WWSSN, and the enhanced precision of radioactive age dating of rock. El Niño finally gained consensus through the collection of data with the large-scale deployment of better buoys and the strength of computers and models of the oceanic and atmospheric systems. Advancements in atmospheric carbon dioxide detection and atmosphere sampling protocols helped standardize readings leading to the conclusion that carbon dioxide levels in the atmosphere are, in fact, rising and that the carbon dioxide was anthropogenic. The Alvarez groups' development and use of the coincidence spectrometer allowed them to *quickly* analyze the possible iridium concentrations of a huge number of stratigraphic beds, allowing them to show that such beds were anomalous and were indeed the remnants of an extraterrestrial impact.

Fifth, we discussed how explanatory models gained consensus because they accounted best for the collected data. Plate tectonics gained consensus prior to our ability to measure plate movements directly via satellites, but now these measurements record actual displacement. For the ENSO phenomenon, meteorologists utilized computer models to successfully predict long-term weather patterns. For the dinosaur extinction event, the discovery of anomalous iridium layers and most importantly the Chicxulub crater both of which coincided with the end of the Cretaceous were the critical evidences that could only be accounted for by an extraterrestrial impact. Ice cores and tree rings have provided evidence of the greenhouse gas profiles of the earth's past; combined with measurements of present-day gas analyzers and the power of computer modeling, it is possible to predict future planetary warming trends.

A final point we would like to make has to do with the nature of controversy resolution. In analyzing the drift controversy, Frankel (1987, pp. 204–205) argued that "Closure of the controversy comes about when one side enjoys a recognized advantage in its ability to answer the relevant questions…when one side develops a solution that cannot be destroyed by its opponents." For the four controversies described here, we note the overwhelming ability of one model to explain the observations that allowed it to garner consensus from the scientific community. When discussing the *Great Devonian Controversy*, Rudwick (1985) asserted that it was one of the most important and influential controversies in the history of geology. Yet, he also claimed that the controversy is virtually unknown to geologists today. "The paradox has a simple explanation. The controversy has slipped out of sight for the good and adequate reason that the problems it raised were eventually resolved in a way that satisfied almost all participants" (p. xxi). Controversies surrounding the origin of oceans and continents, a meteorite impact causing a mass extinction occurring at the end of the Cretaceous period, and the interaction between the ocean and the atmosphere affecting weather around the world are all considered settled to the satisfaction of most of the interested parties. Where anthropogenic global climate change is no longer a controversial issue for those in climate science and indeed most of the scientific community, there continues to be a lag in consensus among much of the US population.

As we have intimated in the beginning of this chapter and as was evident throughout the discussion, there has been very little published concerning the incorporation of HPS into geoscience instruction. There are small pockets of those who continue to promote the efficacy of using cases as a pedagogical tool for teaching science (For examples, see http://sciencecases.lib.buffalo.edu/cs/, http://www1.umn.edu/ships/, http://www1.umn.edu/ships/, and http://hipstwiki.wetpaint.com/page/hipst+developed+cases). A survey of the three case repositories highlighted above (NCCSTS, SHiPS, and HiPST) shows that of the more than 500 cases housed in these three sites, both contemporary and historical, 24 are earth science related. There are six focused on global climate change. Only one of the 24 cases had any relevance to plate tectonics, and even then tectonics was treated as peripheral to the case. There were none focusing on El Niño nor were there any highlighting the dinosaur extinction controversy. A review of the use of case studies is outside the realm of this chapter, but suffice it to say that of the different types of cases available to use, the interrupted case (Herreid 2007) is probably the easiest to implement and still allows much control to the instructor. See Leaf (2011) for an example focusing on Keeling and the measurement of atmospheric CO2. We gave a brief structure to how one might utilize various activities, original documents, and historic and current data as a way to facilitate student model building for plate tectonics.

Aside from the few publications documenting HPS use as an instructional tool, there are even fewer empirical studies investigating the efficacy of such a tool. One possible avenue to remedy this situation is the development and use of historic case studies (Allchin 2011). This would require collaboration among historians and philosophers of science, geologists, and science educators to develop and test such curriculum materials for teaching.

The main point here is not only is there a need to create such tools for teaching that utilize the history and philosophy of science in instruction, but there is also a need for rigorous evaluation and publication in such journals as the *Journal of Geoscience Education* or *Science & Education.* This would give access to practitioners in the field who can further refine them, enhance their own teaching, and ultimately develop students' useful understanding.

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Part VI
Pedagogical Studies: Astronomy

Chapter 19
Perspectives of History and Philosophy on Teaching Astronomy

Horacio Tignanelli and Yann Benétreau-Dupin

The didactics of astronomy is a relatively young field with respect to that of other sciences. In particular, the didactic of astrophysics is barely sketched. Historical issues have most often been part of the teaching of astronomy, although that often does not stem from a specific didactics. Many astronomy textbooks address the historical development of this science, at least anecdotally. Beyond listing historical discoveries and the name and dates of astronomers, textbooks often recount a few specific episodes of the history of astronomy. On the other hand, texts that are essentially historical are devoted to biographical data and/or the relevant cultural and intellectual context of the life and work of astronomers. Their main goal is not to convey scientific knowledge. They assume that the reader who studies the history of a particular science is already aware of the basic ideas of that science. Such studies generally do not aim at assessing the relevance of history for education.[1] Textbooks for the specific teaching of astronomy are typically not structured around its history, let alone the philosophical issues to which its historical development gave rise – at least at the primary of secondary level. Many educational systems assume that the teachers will articulate the connection between the field and its history. The flow of articles on astronomy education in professional journals is minimal when compared to other sciences. The teaching of astronomy is often subsumed under that of physics. One can easily consider that, from an educational standpoint, astronomy requires the

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[1] For instance, *Journal for the History of Astronomy* (the only journal devoted to the subject) has not published works on education (except a few on the history of astronomy education) in its first 40 years of activity.

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same mathematical or physical strategies as physics. This approach may be adequate in many cases but cannot stand as a general principle for the teaching of astronomy.

This chapter offers in a first part a brief overview of the status of astronomy education research and of the use of the history and philosophy of science (HPS) in astronomy education in particular. In a second part, it attempts to illustrate some possible ways to structure the teaching of astronomy around its historical development (ancient and contemporary) so as to pursue a quality education and contextualized learning that contributes to approaching science in its cultural environment. We chose to give priority to those areas of the history of astronomy that clearly illustrate significant conceptual and methodological processes and breaks that are relevant not only to this field but also to other disciplines or to science in general.

19.1 Astronomy Education Research, Reform-Based Teaching, and the Role of HPS

19.1.1 Astronomy Education Research and Reform-Based Teaching

Astronomy is a very popular subject. College-level courses are well attended (Deming and Hufnagel 2001): roughly 10 % of all US college student take an introductory astronomy course while in college (Partridge and Greenstein 2003). After decades of space missions and technological progress, the latest space telescopes and planetary missions continue to capture the public's attention. The historical debates around the evolution of the understanding of the structure of the Solar System are among the most discussed to illustrate key aspects of the nature of science (McComas 2008), and the teaching of astronomy is often done in part through an introduction to its historical development. And yet, there is no extensive study, textbook, or other scholarly manual that covers a wide range of cases and practices – and even very little discussion among astronomy educators – on the role of HPS for the teaching of astronomy, whether it be at the primary, secondary, or college level. Research in astronomy education is itself at an early stage, and in the past decades, major guidelines in science education[2] have been written without the substantial participation of astronomers. Research on the teaching of astronomy is often subsumed under that of physics or mathematics. Consequently, the specific treatment of the teaching of astronomy is relatively scarce.

Yet extant research shows that misconceptions about basic astronomical facts are particularly prevalent among students of various age groups[3] and sometimes among

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[2] Such as *Project 2061* (AAAS 1990, 1994, 2001).

[3] See e.g., on basic notions in astronomy, Taylor et al. (2003), Baxter (1989), Nussbaum (1979), Taylor, or Vosniadou and Brewer (1992) at the primary level, and Diakidoy and Kendeou (2001) and Kikas (1998) at the primary and secondary levels. On more general notions, see Sadler et al. (2010) at the primary and secondary levels, Trumper (2001a, b) at the high school level, and Comins (2000), LoPresto and Murrell (2011), Trumper (2000), Zeilik and Morris (2003), Zeilik et al. (1997, 1998) at the college level.

teachers if they are not well-enough trained in astronomy[4] or in identifying their students' misconceptions (Sadler et al. 2010). There is still relatively little research and resource on pre- and in-service astronomy teachers compared to what is done in physics education.[5] Yet, over the last two decades, and particularly after the work of the Center for Astronomy Education Research[6] has resulted in several doctoral dissertations (Slater 2008), research has shown that evidence supports reform-based teaching of astronomy, with an emphasis on inquiry-based, interactive engagement directed toward conceptual understanding and model-building, whether it be at the at the primary level (Osborne 1991; Taylor et al. 2003), secondary level (Richwine 2007; Hake 2002, 2007), or college level.[7]

However, at the pre-college level, astronomy is often absent in science curriculum and has been so for much of the twentieth century (Jarman and McAleese 1996; Trumper 2006). The teaching of astronomy faces specific challenges:

1. A traditional classroom setting is seen as offering limited opportunities for hands-on, introductory activities in astronomy.[8]
2. Little pedagogical resource exists on the conceptual history of astronomy (particularly at the pre-college level).
3. Primary- and secondary-level educators seldom have sufficient training in astronomy since they do not have to teach astronomy as a separate discipline, but only as a minor part of the physics, Earth science, or geography curriculum.

Nevertheless, astronomy education as a field of research is rapidly growing and has particularly been growing for the past 20 years. It can build up on two decades of work (see Bailey and Slater 2003 and Lelliott and Rollnick 2010 for a review of the existing research literature).

Building on the Force Concept Inventory for Newtonian Mechanics (Hestenes et al. 1992), concept inventories for astronomy education have been developed, particularly for college-level introductory astronomy courses for non-major students (Astro 101 course, see Partridge and Greenstein 2003; Slater and Adams 2002):

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[4] For studies on preservice elementary teachers, see, e.g., Frède (2006, 2008), Trumper (2003), Bayraktar (2009), Schoon (1995), and Trundle et al. (2002) on the understanding of Moon phases; Atwood and Atwood (1996) on the seasons; Bulunuz and Jarrett (2009) for both phenomena; and Atwood and Atwood (1995) on the night and day cycles. For studies on in-service elementary or secondary teachers, see, e.g., Parker and Heywood (1998) or Sadler et al. (2010).

[5] On this topic, see in particular Slater (1993). Work done by the Conceptual Astronomy and Physics Education Research (CAPER) group, based at the University of Wyoming, aims at developing strategies, materials, and resources to support astronomy teaching (inquiry-based in particular) and assess the effectiveness of teaching strategies. See http://www.uwyo.edu/caper/.

[6] This research group is based at the University of Arizona. See their Web site http://astronomy101.jpl.nasa.gov/.

[7] See Hake (2002, 2007), Prather et al. (2009a, b), Rudolph et al. (2010), and Waller and Slater (2011).

[8] In an urban environment in particular, light pollution constitutes a major obstacle to an easy introduction to the stars.

For the high school and college levels:

1. The Astronomy Diagnostic Test (ADT) assesses students' background knowledge (Adams et al. 2000).
2. More recently, following the work of the ADT, the Test of Astronomy Standards (TOAST) is an assessment instrument for conceptual diagnostics and content-knowledge surveys. It is aligned to the consensus learning goals stated by the American Astronomical Society – Chair's Conference on ASTRO 101, the American Association of the Advancement of Science's Project 2061 Benchmarks (AAAS 1994), and the National Research Council's National Science Education Standards (NRC 1996) (see Slater and Slater 2008).
3. The Light and Spectroscopy Concept Inventory touches on the properties of light, the Stefan-Boltzmann law, Wien's law, the Doppler shift, and spectroscopy (see Bardar et al. 2007 and Schlingman et al. 2012 for an assessment).
4. The *Astronomical Misconceptions Survey* (LoPresto and Murrell 2011) provides a 25-question survey aimed at assessing college students' misconceptions, based on the work done by Zeilik and colleagues (see Zeilik et al. 1998; Zeilik and Morris 2003).
5. The Lunar Phases Concept Inventory (Lindell and Olsen 2002) probes high school and college students' understanding of the cause, motion, and period of Lunar phases through 28 questions.
6. Star Properties Concept Inventory (Bailey 2007; Bailey et al. 2012) covers temperature, luminosity, mass, formation, and fusion with 25 questions.

For the K-12 level, *The Astronomy and Space Science Concept Inventory*, a broader 211-question survey has been developed by Sadler et al. (2010), particularly designed to match NRC Standards and AAAS Benchmarks.

Those concept inventories, which are meant to allow one to measure the progress of students' and teachers' understanding or the effectiveness of teaching methods (Bailey 2009),[9] only marginally assess students' knowledge of the historical development of astronomy. Assessments of the effectiveness of a concept-based teaching of astronomy through its historical development are even absent in astronomy education literature reviews (Bailey and Slater 2003; Lelliott and Rollnick 2010, or Pasachoff and Percy 2005) and are yet to be carried out. The case can be made that if such assessments were to be pursued, the already existing concept inventories should be used a standardized benchmarks (Brissenden et al. 2002).

Among these different concept-centered approaches to astronomy teaching, there does not seem to be a clear and explicit consensus as to what role the history of astronomy should play, even though the discipline, if taught separately, is often introduced through reference to its historical development.[10] For instance, at the

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[9] See Libarkin (2008) and Wallace and Bailey (2010) for a discussion on the relevance of these surveys and the effect of, e.g., sample size in the ability of concept inventories to be used as measuring tools.

[10] A fine (albeit dated) example of a college-level introductory book for liberal arts students that incorporates a large amount of historical details can be found in Payne-Gaposchkin and Haramundanis (1956). A recent college-level introductory textbook in astronomy such as Morison (2008) shows that textbooks for astronomy or physics majors can also largely revolve around the historical development of observation techniques and scientific discoveries.

college level, whereas Partridge and Greenstein (2003) consider that an acquaintance with the history of astronomy is one of the main goals of an introductory class in astronomy, a concept-centered introductory textbook such as Zeilik (1993) contains very little historical information.

19.1.2 General Resources in Astronomy Education

The recent article by Waller and Slater (2011) concisely sums up the history of developments in astronomy education.[11] Certain elements of this survey can be emphasized and a few remarks on resources in astronomy education can be added:

1. *Astronomy Education Review* is one of the very few publications dedicated to astronomy education. Historical or philosophical concerns are not at the core of its mission, even though they are sometimes addressed. It is freely accessible, published online by the American Astronomical Society since 2001.[12] According to Lelliott and Rollnick (2010), over the period 1974–2008, "[n]early a quarter of the articles [on astronomy education] were published in the *International Journal of Science Education*, while *Science Education* and the *Journal of Research in Science Teaching* together account for a further quarter." Thanks in part to *Astronomy Education Review*, the flow of astronomy education research articles is rapidly increasing as a research community is growing.
2. The National Science Foundation has recently funded a joint project called Communities for Physics and Astronomy Digital Resources in Education (ComPADRE),[13] which provides reviewed and annotated resources for those teaching introductory courses in both physics and astronomy.
3. The Searchable Annotated Bibliography of Education Research (SABER), an online database in astronomy education supported by the American Astronomical Society, is available at http://astronomy.uwp.edu/saber/.
4. The Commission No. 46 of the International Astronomical Union on the teaching of astronomy[14] constitutes an essential resource and centralizes publications and announcements of the different groups and events that promote communication, education, and development of the history of astronomy. Published on the occasion of the UNESCO-sponsored International Year of Astronomy in 2009, the 2010–2020 strategic plan *Astronomy for the Developing World*[15] gives an overview of the objectives and projects of the IAU for developing the education of astronomy. It lists the history of astronomy as one of the principal areas to pursue, but offers little guidance as to why and how to do so.

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[11] It is to be noted that historical approaches in astronomy education are not mentioned.

[12] A review of its first years of activity can be found in Wolff and Fraknoi (2005).

[13] http://www.compadre.org

[14] See http://www.iau.org/education/commission46/ A brief review of the educative actions carried out by the IAU can be found in Isobe (2005).

[15] http://iau.org/static/education/strategicplan_091001.pdf

5. Likewise, the Commission No. 41 of the IAU on the history of astronomy is a valuable source. Its Web site[16] offers notes, proceedings of conferences, and event announcements of the various working groups of this Commission (Historical Instruments, Astronomy and World Heritage, etc.).
6. The Commission No. 55 of the IAU, "Communicating Astronomy with the Public," has been publishing its journal for a few years now, starting in 2007. The *CAP journal* aims at supporting formal and informal astronomy education. The presence of articles on the history of astronomy shows its relevance for the popularization and divulgation of astronomy.
7. For the development of teaching of astronomy at the IAU, the colloquia No. 162 "New Trends in Astronomy Teaching" (Gouguenheim et al. 1998) and No. 105 on "The Teaching of Astronomy" (Pasachoff and Percy 1990) were major landmarks (see also Swarup et al. 1987). They were followed by a conference held on July 24–25, 2003, on "Effective Teaching and Learning of Astronomy" as part of the 25th General Assembly of the IAU, which resulted in the publication of a book (Pasachoff and Percy 2005). It presents an evaluation of the state of research in astronomy education, available resources and educational programs, and teaching practices. In it, historically informed, concept-based education is presented as being in a preliminary stage.

A few regional organizations and publications on astronomy education can be emphasized:

1. The European Association for Astronomy Education (EAAE) was constituted in Athens on November 25, 1995. The aims of the EAAE refer to those named by the Declaration of the EU/ESO workshop at the ESO Headquarters in Garching on Teaching of Astronomy in Europe's Secondary Schools in November 1994.[17]
2. The Euro-Asian Association of Astronomy Teachers[18] was constituted in November 11, 1995.
3. The *Bulletins of Teaching of Astronomy in Asian-Pacific Region,* directed by Syuzo Isobe, started in 1990 and continued for at least 12 years and has featured many articles on astronomy education in Eastern countries.
4. In Latin America, to fulfill the absence of a specific publication of astronomy education and to be a forum to show the Latin-American activity in this area, the peer-reviewed online journal *Revista Latino-Americana de Educação em Astronomia*[19] has been published since 2004, with contributions in Spanish, Portuguese, and English.
5. A few publications on astronomy education, particularly addressing the role of the history of science in science teaching, are available in French. The *Cahiers Clairaut*, edited by the French organization Comité de Liaison Enseignants-Astronomes

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[16] http://www.historyofastronomy.org/

[17] http://www.eaae-astronomy.org

[18] http://www.issp.ac.ru

[19] http://www.relea.ufscar.br

(CLEA),[20] regularly offers practical activities for the classroom centered on historical experiments in astronomy, as well as scholarly work on the history of astronomy. Pierre Causeret (2005), member of the CLEA, has compiled a book on easily reproducible experiments for the classroom for the primary and secondary levels, some of which are historical experiments. A similar approach has been developed for the secondary level by the French organization Planète Sciences (2009).

19.1.3 Roles of HPS in Science Education and Astronomy Education

With its rich history and its methodological particularities (unlike in many other sciences, astronomical objects are not directly manipulable), astronomy courses constitute a good opportunity to raise epistemological questions and discuss general characteristics of science. Educators at the college level are particularly aware that introductory astronomy courses can play such a role for non-major students, some of whom may not take other science courses (Partridge and Greenstein 2003). Even when astronomy is only taught within the framework of other scientific disciplines – as is most often the case at the primary and secondary levels – astronomy provides a context in which questions about the nature of scientific knowledge and practices are particularly relevant. However, whereas a concept-based approach to astronomy teaching is receiving much attention, the specific role and efficiency of the study of the history of astronomy in contemporary classrooms has not been at the center of extensive scholarly works yet.

The case for the inclusion of HPS content in science education to teach the scientific content as well as aspects of the nature of science has been made for decades.[21] The teaching of science through its historical and conceptual development fulfills the goals of a liberal education. Advocates of this approach argue that it promotes critical thinking and allows students a better understanding of the nature of scientific knowledge and practices, as well as scientific knowledge itself. Moreover, teaching science through its history can help humanize scientists and their work, thereby making science more appealing to more students (see Clough 2011). The belief that there is positive value in teaching the history and philosophy of science is supported by major science education organizations (AAAS 1990, NRC 1996, 2011), drawing on empirical studies already made decades ago for the Harvard Project Physics and the History of Science Cases for High School (see e.g., Klopfer 1969; Klopfer and Cooley 1963). More recent frameworks for K-12 science teaching in the United States (NRC 2011) put an emphasis on model-based teaching (Hestenes 1987). The

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[20] http://acces.ens-lyon.fr/clea/

[21] See, e.g., Arons (1965), College of the University of Chicago (1949, 1950), Conant (1948), Conant and Nash (1957), Hobson (2003), Holton and Brush (1985), Holton and Roller (1958), and Matthews (1994).

role of HPS as a useful resource for model- and concept-based science teaching at the core of these more recent frameworks has been articulated by Duschl and Grandy (2008). In particular, these works support the role of the teaching of historical scientific transitions as a way to articulate the conceptual underpinnings of a discipline.

Teaching a scientific domain through its conceptual and historical evolution is consistent with constructivist methods,[22] according to which the teaching of science consists in creating a conceptual change among students (Carey 2000; Dedes and Ravanis 2009; Posner et al. 1982). Teaching the conceptual changes that scientists had to go through throughout history, by overcoming the limitations of previously held beliefs, can help explicitly address the students' own misconceptions (Carey 2009; Nersessian 1992, 2008).

19.1.4 The Role of Historical Cases in Astronomy for Teaching Aspects of the Nature of Scientific Knowledge and Practices

Drawing on millennia of history and specific methodological challenges, the appeal of astronomy for the teaching of aspects of the nature of scientific knowledge and practices is clear. Indeed, historical debates around the evolution of the understanding of the structure of the Solar System are among the most discussed to illustrate key aspects of the nature of science, as has noticed by McComas (2008) who listed several historical cases in a variety of scientific fields, extracted from popular books on the nature of science (see Table 19.1). Other historical cases of astronomy introduced for their relevance for teaching aspects of the nature of science at the college level have been presented on the Web site The Story Behind the Science (see Clough 2011).[23] This Web site covers a few cases in physics, chemistry, and other disciplines, among which astronomy. Similarly, the resource center for science teachers using Sociology, History and Philosophy of Science,[24] at the University of Minnesota (Allchin 2012), contains a few course modules around historical cases in astronomy for secondary- and college-level courses.

The following table, mostly adapted from McComas (2008), isolates the cases that touch on the history of astronomy (broadly construed):

McComas's brief survey of historical cases in astronomy in popular, introductory books on the nature of science shows that in spite of an important presence of astronomy relative to other sciences in such books, most of these cases originate from a narrow period in history. Indeed, more recent cases, particularly in astrophysics, are less approached in such books on the nature of science. This is not typical of the historical cases approached in college-level introductory books in

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[22] We are not here referring to radical, relativist interpretations of the term "constructivism". See, e.g., Matthews (2002) for an appraisal of constructivism in science education.

[23] Michael P. Clough ed. http://www.storybehindthescience.org/

[24] http://www1.umn.edu/ships/

Table 19.1 Survey of historical cases in astronomy used to illustrate key aspects of the nature of science in popular books, mostly as they are presented in McComas (2008). A few suggestions as to how such a table could be expanded have been inserted (in brackets), as well as indications about the appropriate teaching level for each of those cases (*PL* primary level, *SL* secondary level, *HEL* higher-education level)[a]

	Historical cases	Teaching level		
		PL	SL	HEL
1	Galileo quantified and qualified his observations through recorded data. He observed and recorded the positions of Jupiter's moons. He could then predict the future positions. When questioned by the scientific community, he could confirm his observations (Chalmers 1999)	x	x	x
2	Galileo argued in favor of the Copernican view of the universe but his work was challenged by more conservative (traditional) thinkers not because his observations and calculations were found wrong but because his argument was based on observation and calculations, not theoretical understanding. (Thompson 2001). This illustrates the role of alternative theories, interpretation of observations, and the cultural context of science (religion, patronage, politics) (Allchin 2012)		x	x
3	A train of events led to the discovery of Neptune with Le Verrier and Adams suggesting an undiscovered planet near Uranus (Chalmers 1999; Derry 1999). It illustrates how anomalies drive scientific inquiry (Clough 2011) [see also this chapter]	x	x	x
4	Once the heliocentric model was accepted, observations were consistent with what the model suggested (Cromer 1993)	x	x	x
5	Variations in Venus' brightness called into question the Earth-centered model (Cromer 1993)			x
6	Copernicus used the data (evidence) provided by Ptolemy in his models but interpreted the evidence quite differently (Cromer 1993)		x	x
7	Brahe was the first modern astronomer to keep detailed night-by-night records of his observations (Cromer 1993)	x	x	x
8	The effects of gravity on light, predicted by Einstein's theory of relativity, was observed in Africa and South America in 1919 (Thompson 2001)		x	x
9	Galileo performed experiments in front of peers to validate his results (perhaps dropping balls from the Tower of Pisa); he invalidated Aristotle's laws of motion in public areas (Chalmers 1999)		x	x
10	Newton's laws of gravitation and his astronomical observations allowed him to predict planets' positions (Okasha 2002)	x	x	x
11	There is no way to examine all bodies in the universe; therefore Newton used induction in the development of his laws of motion (Okasha 2002)		x	x
12	The shift in understanding from Newton to Einstein is an example of a scientific revolution (Chalmers 1999)			x
13	Galileo suggested that the Earth revolved around the Sun; he was never able to fully substantiate his notion (Sardar and Loon 2002)	x	x	x
14	Brahe refuted Copernicus' theory, but even Brahe's estimates of the distance to the stars were too small (Chalmers 1999)			x

(continued)

Table 19.1 (continued)

	Historical cases	Teaching level PL	 SL	 HEL
15	Kepler's view of the Solar System was superseded by a more complete view provided by Newton (Chalmers 1999)		x	x
16	Newtonian mechanics is enhanced by being firmly embedded in a grand theoretical scheme that can be used to accurately describe a vast range of phenomena, from the motion of protons inside a nucleus to expansion of the universe itself (Cromer 1993)		x	x
17	Copernicus produced a better model of the Solar System but made no attempt to explain the motions of the planets (Wolpert 1994)		x	x
18	Ptolemy believed that the Earth was at the center of the universe. While observing, he saw inconsistencies and forced explanation upon them to fit the geocentric model he held (Cromer 1993)	x	x	x
19	Throughout history, many people believed in the geocentric model of the Solar System because of religion's authority (Cromer 1993)	x	x	x
20	The Church banned books explaining Copernicus' suggestion that the Sun was at the center of the Solar System (Okasha 2002)		x	x
21	Aristotle was deemed such an authority that it was difficult for Copernicus or Galileo to challenge his views (Thompson 2001)		x	x
22	The space race (and the resulting increases in science and technology) between the US and USSR was very much a political (more than scientific) activity (Dunbar 1995)		x	x
23	In Newtonian science, the law of gravity was a fundamental principle; it explained other things but could not itself be explained (Okasha 2002)			x
24	The invention of the telescope allowed Galileo to change Copernicus' ideas about the size of Venus and Mars (Chalmers 1999)	x	x	x
25	New instruments promoted the careful examination of the world. The telescope was improved by Galileo and used to a controversial effect to show sunspots on the "perfect" sphere of the Sun Thompson 2001)		x	x
26	The application of spectroscopic analysis to the stars by Kirchhoff and Bunsen opened a new field of inquiry: the physical analysis of the properties and composition of the stars (astrophysics). It is an example of the role of collaborative work, instrumentation, and puzzle-driven scientific research (Allchin 2012)		x	x

27	The detection of black holes as an example of the power of robust theory and mathematics (Clough 2011)			x
28	The story of the Cosmic Microwave Background as an illustration of how data makes sense only in light of theory (2011)			x
29	The story of Dark Matter as an example of the role of imagination and invention in science. (Clough 2011)			x
30	The debate around the measurement of the size of our galaxy, revealing the role of theoretical assumptions, the dynamics of scientific debates, and the role of technology in discoveries (Clough 2011)			x
31	[The discovery of dark energy as a purely observational result that completely changed our understanding of the large-scale properties of the universe]		x	x
32	[In 1951 the Roman Catholic Church supported the Big Bang Theory]		x	x
33	[The 1925 edition of the "Soviet Encyclopedia" asserted that the theory of relativity is unacceptable for dialectical materialism]			x
34	[Hermann Bondi said that cosmology, whose object of study is the universe as a whole, seems to be immune to observation]		x	x
35	[In 570, Isidore, Bishop of Seville (Spain), distinguishes astronomy from astrology. From then on, scientists must constantly reiterate this distinction]	x	x	x
36	[Copernicus proposed a heliocentric model although no stellar parallax could be observed]		x	x
37	[Observing the transit of Venus in 1761, Mikhail Lomonosov suspected and detected the presence of the atmosphere of Venus]		x	x

[a] These descriptions of historical cases should not necessarily be taken as assertions, but at least as starting points for inquiry and discussion. For instance, the extent to which Einsteinian physics constitutes a revolution from Newtonian physics may be debatable

Table 19.2 Distribution of the historical cases in Table 19.1, according to what key aspect of NOS they most clearly illustrate. Unlike in McComas (2008), a case can illustrate several aspects. Depending on how each case is treated, a very different distribution could be obtained

Key aspect of nature of science	Historical cases in Table 19.1
1. Science depends on empirical evidence	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 18, 24, 25, 26, 27, 30, 31, 35, 37
2. Science shares many common features in terms of method	2, 3, 6, 7, 10, 11, 15, 16, 17, 23, 26, 27, 28, 29, 30, 34, 35, 37
3. Science is tentative, durable, and self-correcting	2, 3, 4, 5, 8, 9, 12, 14, 24, 25, 29, 31
4. Laws and theories are not the same	4, 5, 11, 15, 16, 23
5. Science has creative elements	3, 6, 8, 11, 12, 27, 29, 37
6. Science has a subjective component[a]	13, 14, 17, 18, 21, 36
7. There are cultural, political, and social influences on science	1, 2, 3, 4, 9, 19, 20, 21, 22, 25, 32, 33
8. Science and technology are not the same, but impact each other	1, 2, 3, 7, 24, 25, 26, 30, 31, 37
9. Science cannot answer all questions (science has limitations)	3, 11, 23, 34

[a] This category is here taken as meaning that scientists' personal preference or bias can have an influence on their research

astronomy and astrophysics, whose primary goal is not to teach about the nature of science. McComas divides these examples in nine categories, placing each case in a unique category corresponding to a key tenet of nature of science (NOS) it best illustrates. Table 19.2 above suggests a distribution of these cases according to such tenets of NOS, a domain-general, consensus-based list of aspects of NOS (see, e.g., Lederman et al. 2002; McComas and Olson 1998). Such lists are widely used in science education research but are not uncontentious, as they run the risk of promoting an essentialist view of science and confusing epistemological, ontological, and metaphysical features of science (Eflin et al. 1999; Duschl and Grandy 2012).[25]

This list of key aspects of NOS does not easily allow one to characterize methods of inquiry that are specific to a discipline or a type of inquiry. In general, they may not allow one to fully appreciate the historical, philosophical, and scientific relevance of each case.[26] Indeed, the examples in Table 19.1 can be illustrative of more meaningful aspects of scientific knowledge and practices. For instance, the universality of laws of nature and the role of this feature in scientific inquiry (implied by the tenet "Science shares many common features in terms of method") are more specifically

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[25] The proponents of such lists often deny such intentions (see, e.g., Abd-El-Khalick 2012). The consensus around this particular choice of categories is not unanimous (for instance, one may prefer to say that science is provisional rather than tentative or refuse to equate subjectivity with theory-ladenness as is sometimes done).

[26] Instead, Eflin and colleagues "recommend illustrating the rich complexity of science with its practice and its history. Such study will offer students a better picture of the complex family resemblances between all the activities we call science" (Eflin et al. 1999, p. 114).

exemplified by cases 3, 10, 11, 16, 26, 27, 28, and 30. Moreover, the social responsibility of scientists (here illustrated by case 35) cannot not clearly figure in such a list of aspects of NOS. Nonetheless, the proponents of such nomenclatures hope that they may at least constitute a synthetic, introductory way of underlining the philosophical relevance of such historical cases in science and spark curiosity about what can be called science and why.

19.1.5 Gender Mainstreaming

The history of astronomy is relatively rich in major contributions made by women scientists. Marilyn Bailey Ogilvie's biographical dictionary (1986) lists only 180 women scientists, from antiquity to the beginning of the twentieth century. Although this list is not exhaustive, it can give us an indication of the relative contribution of women to science. It is interesting to note that astronomy is the second most represented discipline in that census (after biology). Nowadays, although there are thousands of women astronomers, they only account for about 16 % of the members of the IAU.[27] Omitting to include in the astronomy curriculum the contributions of women astronomers would only perpetuate a fragmentary and biased teaching. A historically informed teaching of astronomy can help students acknowledge the too-often overlooked contributions of women scientists to astronomy. It can reveal the struggle of women astronomers and illustrate the importance of the cultural context in scientific discoveries, the sociological organization of the scientific community, or counter the stereotypical image of science as being a masculine discipline.

To that effect, a few emblematic historical cases can be emphasized:

1. In ancient Babylon, EnHeduAnna (circa 2300 B.C.), as other priestesses in ancient cultures, performed astrological and astronomical tasks jointly. She enjoyed considerable political influence and is also remembered as a poetess (Meador 2009).
2. In ancient Greece, Aganice of Thessaly (second century B.C.), mentioned in the writings of Plutarch, was an expert in Lunar eclipses. Hypatia of Alexandria (circ. 370–415), the most noted woman scientist in ancient Greece, made major contributions not only to astronomy but also to mathematics and philosophy (Alic 1986).
3. In modern times, the Silesian astronomer Maria Cunitz (1610–1664), who simplified Kepler's planetary tables; the French astronomer and mathematician Nicole-Reine Lepaute (1723–1788), who calculated the orbit and date of return of several comets (including Halley's); the famous Caroline Herschel (1750–1848), one of the most acute observers in astronomy of the nineteenth century, discoverer of comets and nebulae; Maria Mitchell (1818–1889), the first American woman to work as a professional astronomer; and Agnes Mary Clerke (1842–1907), an Irish historian of astronomy.

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[27] Source: http://www.iau.org/administration/membership/individual/distribution/.

In the twentieth century, thanks to the pioneering work of women astronomers in America such as Annie Jump Cannon, Henrietta Leavitt, Williamina Fleming, and the famous astrophysicist Cecilia Payne-Gaposchkin or that of the British astronomer Jocelyn Bell, women astronomers worldwide burst on the scene of the scientific investigation of the universe. Several works are available as a resource on the life and contributions of recent or contemporaries women astronomers.[28] However, only few such publications have been written for the classroom.[29]

19.1.6 The Role of HPS for the Teaching of Astronomy

In spite of these resources, the rationale behind the role of HPS in astronomy teaching in particular – to teach not only aspects of the nature of science but also *scientific content itself* – has not been fully fleshed out yet. For instance, in spite of the IAU's interest in education, the role of the history and philosophy of astronomy is particularly underdeveloped within its meetings and publications.[30] Since astronomy is not systematically taught at school – and rarely as a separate topic except at the college level – astronomers and astronomy educators sometimes have to remind that astronomy is useful and should be included in the school curriculum (Percy 2005). The fact that the astronomy education research community is relatively new and that the teaching of astronomy (at the primary and secondary levels at least) is subsumed under that of other disciplines (physics, geography, Earth science) may explain why only few works explicitly address the role of historically centered teaching in astronomy,[31] let alone measure its effectiveness on student learning. More than half a century after its development, Harvard Project Physics remains one of the most exemplary source of educational material on the integration of HPS content for teaching astronomy.[32]

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[28] See, e.g., Byers and Williams (2006), Gordon (1978), Johnson (2005), Mack (1990), and Rossiter (1982). For an introductory resource guide to materials on women astronomers available on line, see Fraknoi (2008).

[29] See in particular two Web sites: Harvard University Libraries and Museum, Open Collection about "Women Working, 1800–1930", http://ocp.hul.harvard.edu/ww/index.html, and Woman Astronomer: http://www.womanastronomer.com.

[30] For instance, in their review of the papers on astronomy education presented at the IAU's meetings between 1988 and 2006, Bretones and Neto (2011) found that only 4.9 % of the 283 papers that dealt with astronomy education (i.e., only 14 papers) belonged to the category "studies on history of Astronomy or history of Astronomy Education."

[31] In particular, we can point out to the lesson plans accessible on the ComPADRE Web site (http://www.compadre.org) and to Hirshfeld (2008), which offers a collection of paper-and-pencil, interactive activities aimed at reproducing historical experiments.

[32] Some documents developed for Project Physics cover the history of our understanding of the structure of the Solar System and the motion of the planets. Astronomy was not the main subject covered by this project. Textbooks, documents for the classroom, and tests are accessible on http://archive.org/details/projectphysicscollection.

In their analysis of physics education, Höttecke and Silva (2011)[33] have identified obstacles for including HPS content in the science classroom. These include a culture of teaching science that is different from that of teaching other subjects, issues with the training of teachers (in particular the insufficient training in how to use HPS content), lack of clarity in curricular standards on the role of HPS, and lack of HPS appropriate content in textbooks. As we have seen earlier, in primary and secondary education, the teaching of astronomy exacerbates all these problems. Indeed, teachers are often not sufficiently trained in astronomy, astronomy is viewed in curricular standards as part of another discipline (if at all), and the main guidelines addressing the role of HPS in science education have been developed without a substantial participation of astronomers.

Nevertheless, a case for the inclusion of HPS in astronomy education can be found in a few instances. Such a rationale, when it specifically concerns astronomy education, is not different from what exists for other disciplines: teaching the history of science humanizes scientific research and practice and makes science more palatable and less intimidating (Partridge and Greenstein 2003; Zirbel 2004), and in particular, a universal history of astronomy helps avoid a Western-centered teaching (see Kochhar in Greve 2009). The role of HPS in astronomy education for concept-based teaching has been alluded to by Zirbel (2004), who remains cautious:

> It can be hypothesized that students learn concepts in a manner similar to the way that society learns basic concepts. It also turns out that a historical approach tends to be the least intimidating to students because they see the mistakes of humanity and of some famous individuals. This can make science less dry and more approachable, and make students more confident. For example, Duschl (1992) suggested that science instruction might benefit from a constructivist-historical approach in which students learn not only the justifications of modern scientific theories, but also how and why older theories where rejected, and how the nature of scientific inquiry changed within the discipline when the scientific community shifted from the old paradigm to the new. Other studies even went as far as to claim that the developmental stages in children (described by Piaget in 1929) can be simulated through historical parallels (e.g., Sneider and Ohadi 1998). (Zirbel 2004)

In their presentation of the goals for the concept-based course Astro 101, Partridge and Greenstein (2003) are more explicit with regard to the usefulness of HPS for a concept-based teaching of astronomy. They present the “acquaintance with the history of astronomy and the evolution of scientific ideas (science as a cultural process)” as one of the key content goals of an introductory astronomy college-level course. This recommendation, they say, is “self-evident” because it renders the discipline more appealing, illustrates aspects of the nature of science, but also because “the history of astronomy provides wonderful examples that illustrate some of the [other] goals” regarding content knowledge, skills, values, and attitudes.

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[33] Their work is part of the European project HIPST (History and Philosophy in Science Teaching): http://hipst.eu/.

For instance, the cross-age (elementary to college) study of Kavanagh and Sneider (2007a, b) on student understanding of gravity allows one to see how the historical progression of scientific conceptions of gravitation follows that of students (see also, at the college level, Williamson and Willoughby 2012). However, a more fleshed-out articulation of the role of HPS in astronomy education, on a large variety of topics; the development of canonical examples and teaching practices that include HPS content, at various teaching levels; and an standardized assessment of the specific import of HPS content are yet to be carried out.

19.2 Three Cases as Examples of the Role of HPS for the Teaching of Astronomy

This second part attempts to illustrate possible ways to structure the teaching of astronomy around its historical development. The following examples all deal with the study of planets, a fundamental notion for all levels of astronomy teaching. These historical cases, though not necessarily the most emblematic ones, are possible examples of incorporation of historically and philosophically informed material in the science classroom. These cases are each best suited to different levels and cover contributions from different periods, from ancient times to the most contemporary discussions:

1. The first case deals with Kepler's use of the work of Archimedes and Apollonius for the development of his laws of planetary motions. It focuses on an important event in the history of astronomy – the application of the geometry of ellipses to planetary motion – that also had ramifications in philosophy and mathematics. It is best suited to a high-school-level science or mathematics curriculum.
2. The second case focuses on the social and cultural context of the discovery of Neptune. It also underlines how the confidence in our theories drives scientific inquiry and the importance of accounting for anomalies. It would be most appropriate for primary- or secondary-level teaching.
3. The third case is centered on the recent debate around the planetary status of Pluto. It attempts to show how underlining its philosophical motivations can help understand its relevance for science, and provide an engaging way to strengthen one's understanding of the structure and formation of the Solar System. It is more appropriate for a college-level course.

Table 19.3 below summarizes which aspects of the nature of scientific knowledge and practices these cases emphasize (according to some of the categories of Table 19.2).

Table 19.3 Key aspects of the nature of science illustrated by the three cases presented below in this chapter, based on Table 19.2

Key aspect of the nature of science	1st case	2nd case	3rd case
Science depends on empirical evidence	x	x	x
Science shares many common features in terms of method		x	x
Science is tentative, durable, and self-correcting	x	x	x
Laws and theories are not the same	x	x	
Science has creative elements	x	x	x
There are cultural, political, and social influences on science	x	x	x
Science and technology are not the same, but impact each other		x	
Science cannot answer all questions	x	x	

In addition to this summary, a few additional themes that these cases touch on can be emphasized:

1st case	2nd case	3rd case
Influence of the cultural context		
Geometry was only admitted as a tool with which to represent celestial problems but was not considered to be able to provide solutions to them	The scientist's social background or status was decisive in the process of scientific inquiry	The political organization of professional astronomy had an influence on scientific decisions
Although elliptic orbits constituted a reliable solution, they were considered as inappropriate at the time	Political and academic tensions between European nations ended the paralysis in the search for the new planet	The national sentiment about the only planet discovered by Americans prevented a discussion about the definition of planet to happen sooner
Aspects of the process of investigation		
The problem of accurately describing all planetary orbits was considered to allow for a unique and definitive solution. As such, it has been approached in the same manner since antiquity. Solving it required an obstinate person who changed the way to frame it	Two scientists from different countries came to a unique solution to a common problem, independently from each other	A scientific dispute, motivated by new discoveries, had to be resolved not by consensus but by a vote between scientifically receivable alternatives
A great confidence in empirical results as well as in the method used to analyze them enabled a change of explicative models once considered impossible	The absolute confidence in a theory (Adams, Le Verrier) conflicts with an opportunity to amend it (Newcomb, Hall) or replace it (Einstein)	Classifications are needed as theoretical or explanatory devices, and while they drive investigation, they can be modified as our understanding of the structure of the world evolves

(continued)

(continued)

1st case	2nd case	3rd case
Accounting for observational anomalies in conflict with accepted theories		
A solution was found in a substantial and unexpected change in the geometrical treatment of planetary orbits	The successful application of the hypothetico-deductive method resolved the conflict[34]	A philosophical examination of what is expected from a taxonomy helps us understand the reasons behind the prevailing choice
Other notable themes		
A historically informed teaching can provide a more meaningful, less mechanical understanding of geometry and how it relates to physics	Observation drives and establishes our understanding of the universe (i.e., Herschell)	Disagreement among scientists does not necessarily undermine the validity and authority of their decisions
	The serendipitous intervention of unexpected agents (i.e., Galle, Lescarbault, Gerber) resulted in a clarification of the problem	Other scientific fields (i.e., biology) have had to overcome similar disputes

19.2.1 The Geometry of Planetary Orbits

19.2.1.1 A Circular Ancient Astronomy

Archimedes of Syracuse (287–212) did not leave meaningful astronomical comments, yet his mathematical contributions (mainly those related to geometry) proved to be relevant to Johannes Kepler (1571–1630). In contrast, the mathematician Apollonius of Perga (262–192), a contemporary of Archimedes, played an important role in ancient astronomy. Apollonius inherited from the Greek astronomers the concern to *save the phenomena*: for a kinematic planetary model to be successful, it has to explain the planetary motions as they are observed in the sky (in particular, the apparent retrograde motion). It was Apollonius who:

Developed a model of the universe in which he generalized the epicycles for the planets	According to his model, the planetary orbits are not centered on Earth but on a epicycle whose center is located on another circle (deferent) that revolves around the Earth.[35] A successful combination of these two uniform, circular motions can explain the observed retrograde motion without any need to deprive the Earth of its position at the center the universe

(continued)

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[34] It has been argued that Newton's method and notion of empirical success is richer than just what the hypothetico-deductive model suggests: "According to [Newton's] ideal [of empirical success], a theory succeeds empirically by having its causal parameters receive convergent accurate measurements from the phenomena it purports to explain" (Harper 2002, p. 185). See (Harper 2007) for a study of how the resolution of the problem of Mercury's perihelion shift illustrates this.

[35] Epicycles already featured in the geo-heliocentric model of Heraclides of Pontus (390–310, but they were restricted to two planets only (Venus and Mercury). This model placed the Earth

(continued)

Optimized the idea of eccentric orbits	Placing a planet on a single deferent not centered on Earth could produce the same observable result as placing it on epicycles. The distance between Earth and the new center of the deferent is called *eccentricity*, and then the orbits are called *eccentrics* (Sarton 1959, Chap. V)

Apollonius is also the author of *The Conics* (Heath 1896), an eight-book-long treatise in which are defined and examined in great detail ellipses, parabolas, and hyperbolas, figures who owe him their name. Despite his familiarity with ellipses, Apollonius did not apply or suggest (not even mention) the use of ellipses for studying astronomical questions. The habitual use of circles resulted surprisingly effective in his model of planetary orbits with epicycles and deferents. The adulation for the perfection of the circle was very widespread and entrenched. So much so that, had someone suggested that planetary orbits have the shape of ellipses, Apollonius himself would probably have worked to reduce each proposed ellipse to a combination of circles. Apollonius's astronomical ideas were first adopted by Hipparchus of Nicaea (190–120), and then by Claudius Ptolemy (100–170), who in his treatise *The Almagest* consolidated and established an apparently unquestionable geocentric model.

It took more than 1,400 years until Nicolaus Copernicus (1473–1543) proposed a fundamental change in the arrangement of the universe: the Sun would be at the center and the planets (including the Earth) would form a system rotating around it. Copernicus still retained circular orbits, uniform motions, as well as several epicycles. Two decades after the work of Copernicus was published, Tycho Brahe (1546–1601) renewed and refined his observation procedures, which yielded records of planetary positions of higher precision. With them, Brahe suspected that the Copernican (heliocentric) model should be replaced by a new proposal that he imagined to be geo-heliocentric.[36] So he summoned Kepler to assist him in finding a mathematical justification for his idea.

19.2.1.2 Kepler, Orbit-Maker

From Apollonius (and even before him) to Kepler, no figure and model of the universe accepted by astronomers and mathematicians had ever challenged the dominance of the circle and sphere. This principle superseded other aspects of scientific inquiry and slowly became a moral premise that dictated the conduct of the celestial bodies themselves. Kepler recklessly overcame this prejudice and constructed the best possible model for planetary orbits: one that was faithful to the observed

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(rotating on its axis, in one day) at the center of the universe. The Sun and the Moon (as well as the planets Mars, Jupiter, and Saturn) revolved around the Earth, while Mercury and Venus, instead, revolved around the Sun. Moreover, Apollonius was the one who gave its denomination to the circles that describe planetary motion (epicycle and deferent).

[36] Brahe proposed a model similar to that of Heraclides.

reality. Thereby, Kepler got rid of other (maybe mathematically perfect) models. It is well known that the result, the three Kepler laws of planetary motion, undoubtedly played a significant role in the history of our understanding of the universe. The first two laws were published in his *Astronomia Nova* (1609) and the third one in *Harmonices Mundi* (1619). However, in reality, Kepler constructed his second law before the first (Koestler 1960, p. 137), and their subsequent reorganization was motivated by logical and aesthetic considerations. In other words, Kepler had found that the orbital velocity of the planets was variable before he could describe the geometry of their trajectory around the Sun. With the adoption of egg-shaped trajectories, Kepler was not able to account for the variation in speed of the planets on their orbits. He even hesitated to uphold his famous second law (the only one he had then) to avoid the intellectual choking that would have stemmed from abandoning the beloved circular orbits, defended by Copernicus, whom he admired.

Kepler worked with Brahe's records of the motion of Mars, considering them as precise and irrefutable. He tested various orbit formulations and found that the "oval orbit" was invariably an appropriate solution. It is to be noted that Kepler used ellipses in his approximations as auxiliary computing elements only, in order to determine oval areas in particular. In 1603 Kepler wrote to his friend David Fabricius (1564–1617) and confessed to him that he felt unable to resolve the geometry of his "egg," noting that "if only the shape were a perfect ellipse, all the answers could be found in Archimedes' and Apollonius' work"[37] (Koestler 1960, p. 143). After several years, Kepler even came to conceive a mathematical formulation allowing him to account for the variation of the planets' distance from the Sun on their orbit. However, Kepler could not realize that his expression was in fact defining an ellipse, as he conceived his construction as an *ad hoc* formula, foreign to the set of geometric figures culturally acceptable to describe the motion of planets. Later, Kepler decided to try his luck with other methods, including a purely geometric procedure for describing Mars' orbit. Then, he found that it was in fact an ellipse and, soon after, rediscovered that the previously dismissed expression gave the same result.

19.2.1.3 Kepler's First Law in the Classroom

An important aspect of Kepler's contribution is the introduction of ellipses in celestial geometry, which seemed confined only to circular trajectories, almost from the beginning of that science. After Kepler's laws, Apollonius's conics gradually acquired a special relevance in kinematics and subsequently also in the dynamics of planetary motion,[38] which is something Apollonius could not predict. The cultural

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[37] Letter to Fabricius, July 4, 1603 (Baumgardt 1951, p. 72).

[38] The ellipses in particular but not only them: parabolas and hyperbolas also took on new meaning in study of celestial objects. In fact, the relevance of ellipses extended to other sciences, particularly physics.

significance of the change of shape in planetary orbits made by Kepler (from circles to ellipses) should still deserve to be taught. The enunciation of the first law, as it appears in school textbooks – "The orbits of the planets are ellipses with the Sun located at one focus" – is in general learned unquestioningly, uncritically, and the teacher often swiftly draws students' attention to other laws that seem to be of greater didactic importance, given their physical implications.

Planetary orbits are ellipses…	In many cases, students talk about this conical shape without fully knowing its features, as if knowing its name was enough to understand its properties. When students are not able to consciously assign meaning to words, learning is mechanical, not significant (Moreira 2005, p. 28). For students, the resistance in carrying out the conceptual change about the shape of orbits (from circles to ellipses) may turn out to be very high. In pedagogical terms, the shift from circles to ellipses is as significant as the passage of a geocentric to a heliocentric system
… with the Sun located at one focus	Without a good understanding of the properties of the ellipse the location of the Sun "in focus" is possibly meaningless.[39] However, a proper understanding of this feature opens the doors to students to Newton's ideas, especially the universal law of gravitation (see Goodstein and Goodstein 1996; Haandel and Heckman 2009)

Apollonius and later Ptolemy, after developing a model of epicycles and deferent, adjusted the times of revolution of the planets to their (prefixed, preconfigured, impossible to change) geometries. Kepler, however, walked a reverse route: from observational data, he obtained planetary velocities. Since the observed velocities were nonuniform and thus different from the classically established uniform motions, the inferred trajectories (ellipses) were different from the usually assumed circular orbits.

But in the classroom, students continue to learn the first law as a premise or in some audacious cases as a deduction from the observations. It is not uncommon that although the teacher may emphasize the talent and perspicacity of Kepler in constructing a geometric solution with the ellipse (an unusual feature for the student), this fact is presented as if it were only a happy coincidence, conveniently agreeing with Brahe's observations. No less remarkable is the fact that until the presentation of the Laws of Kepler many students have barely heard of ellipses. Usually, the teaching of the ellipse is notably quite limited.[40] One of the consequences of this is the loss in understanding of much of the potency and depth of Kepler's laws. Thus, many students tend to *recite* the first law with little or no understanding of the importance of this law for the development of science in general and astronomy in particular. With a more adequate teaching of geometry and

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[39] For example, a significant consequence of this feature is that a planet reaches a position of minimum and maximum distances to the Sun (perihelion and aphelion, respectively).

[40] It is not the case with circles, which are dealt with under different perspectives and in different subjects in the classroom. Most often, parabolas are well taught, but merely as a graphical solution to quadratic equations. Hyperbolas on the other hand are merely named, while ellipses constitute only an exercise in graphical construction of figures.

history of science comes a better understanding of many physical phenomena. For instance, here, if we neglect the role of time, Kepler's (dynamic) second law results in the (geometric) first law.

19.2.2 New Science, New Planets?

19.2.2.1 From Fiction to Reality

William Herschel (1738–1822) discovered in 1781 a peculiar celestial object that caught his attention. During his first observations, he thought it was a new comet. However, after a few months, Herschel noticed that its trajectory did not stretch out as was expected of comets (i.e., its orbit remained approximately circular). He soon confirmed that this was an unknown planet, orbiting beyond Saturn. He named it 'Georgium Sidus' (in honor of the king of England), but today it is known as Uranus.[41] Four decades later (1821) the French astronomer Alexis Bouvard (1747–1843) published an astronomical treatise containing information on the trajectories of several planets, after having observed and recorded their positions for years. His data revealed substantial discrepancies when compared to the previously computed orbit of Uranus. Given this evidence, several scientists suggested that these variations could perhaps reveal that the physical laws governing planetary motions were no longer valid beyond a certain distance from the Sun (i.e., beyond Uranus). However, Bouvard postulated that perhaps the differences between Herschel's calculations and his own observations could be due to the presence of an unknown celestial body orbiting the Sun beyond Uranus. This body would disturb the motion of Uranus so that it does not comply with Kepler's laws, without implying any violation of Newton's law of gravitation.[42]

Twenty years later, a young English astronomer, John Couch Adams (1819–1892), dedicated himself to this subject and calculated the mass and orbit of a hypothetical planet revolving around the Sun beyond Uranus, which could explain the anomalies that Bouvard had detected. Adams communicated his results to his teacher, the astronomer James Challis (1803–1882), and to George Airy (1801–1892) at Greenwich Observatory. Initially, Airy did not even attempt to verify this hypothesis but Adam's insistence prompted him to start a survey in order to find the hypothetical planet. This work began in July 1846 in Cambridge, and Challis himself was in charge. Unfortunately, no detection confirming Adams's ideas could be obtained.[43]

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[41] In hindsight it received various denominations (in France was known as *Hercules*) until was finally accepted the suggestion by Johann Bode (1747–1826) to identify it as *Uranus*. Nevertheless Herschel continued to call it *Georgium Sidus*.

[42] The renowned astronomer Friedrich Bessel (1784–1846) supported the scenario described by Bouvard in 1824.

[43] Further analysis of the Challis observational registers showed that he had observed the new planet on the 8th and 12th of August but wrongly identified it as a star.

In France, the same year as when Adams presented his hypothesis of a *transuranic* planet (1845), the astronomer Urbain Le Verrier (1811–1877) presented a similar prediction at Paris Observatory, unaware of Adams's work. Faced with the indifference of his colleagues, Le Verrier presented his calculations about a possible new world again in June and August 1846. He had predicted the mass and specific values of the orbital elements, but once again, his hypothesis was rejected. Finally, Le Verrier communicated with the German astronomer Johann Gottfried Galle (1812–1910), who was then working at Berlin Observatory, and indicated to him where to point the telescope in order to find the planet predicted by his calculations. Galle, together with his pupil – Heinrich d'Arrest (1822–1875) – observed the indicated area and, in less than an hour's work, found the new planet only 1° away from the position predicted by Le Verrier.[44] Immediately, both British and French astronomers claimed to be recognized as the true discoverers of Neptune, by means of mathematical calculations instead of usual astronomical procedures. Nowadays, the discovery of Neptune[45] is customarily attributed to the binational duo Adams-Le Verrier.

19.2.2.2 From Fiction to Unreality

The prediction of the existence of Neptune through mathematical calculations and its subsequent observational discovery where indicated by equations was an unparalleled triumph of Newtonian mechanics and, for many, of the power of science in general. The celestial mechanics of the Solar System seemed fully resolved. However, there was a *small* problem: the motion of Mercury was different from what was expected, as there were some anomalies in the shift of the perihelion of Mercury that could not be explained by Kepler's laws and Newton's law of gravitation.[46] In order to solve this problem, Le Verrier predicted in 1859 that Mercury's orbital perturbations had a similar cause as those previously detected on Uranus. Hence, he suggested that a new planet, unknown so far, was situated between Mercury and the Sun.[47] Quickly, he called it "Vulcan" to prevent future discussions.

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[44] Apparently, as Galle was the first to look through the telescope, he is recognized as the discoverer.

[45] Shortly after, the new planet was simply called *the planet after Uranus* or *Le Verrier's planet*. The first suggestion for a new name came from Galle: *Janus*. In England, Challis suggested *Ocean*. From Paris, François Arago (1786–1853) proposed *Le Verrier* (a suggestion not well received outside of France). Meanwhile, Le Verrier insisted on calling it *Neptune* and received the support of Friedrich Struve (1793–1864) to carry on the tradition of naming planets after mythological figures.

[46] Like other planets, Mercury does not follow the exact same trajectory traced by its previous orbit (this phenomenon is called "perihelion shift"). For Mercury, the observed value of this shift is about 575 arcsec/century; most of it (532 arcsec/century) can be explained by gravitational perturbations from other planets (and to a much smaller degree the Sun's shape – its oblateness). The small difference (43 arcsec/century) could not be accounted for by Newtonian gravity. It was considered an anomaly and was treated as a serious problem of celestial mechanics.

[47] Le Verrier also considered the possibility that instead of a planet would lie a group of small celestial bodies (like an asteroid belt).

The great scientific reputation of Le Verrier was enough to convince most contemporary astronomers of the existence of Vulcan. Its *presence* in the Solar System brought calm to the astronomy community. Again, Le Verrier established the orbital elements of the new planet and its mass. Many telescopes around the world were used to find Vulcan, without success.

All of a sudden came the news that a French amateur astronomer, Edmond Lescarbault (1814–1894), had detected Vulcan. He described it as an opaque body passing over the Solar disk (on March 28, 1859). Having ruled out the possibility of a sunspot, Lescarbault concluded that he had observed a transiting planet. He wrote and narrated his discovery to Le Verrier, which visited him soon after. Even though Lescarbault's transit registers were of poor quality and his instruments rudimentary, he made a very thorough description and in such detail that Le Verrier believed him.[48] Evoking the euphoria experienced with Neptune, Le Verrier announced the discovery of Vulcan (January 1860) to the French Academy of Sciences. The news of the discovery of Vulcan was received with caution by the astronomical community, whose skepticism was only assuaged by Le Verrier's great fame. It was very strange that the new planet was not observed by any professional astronomer at any observatory, with the most sophisticated instruments. Le Verrier recalculated Vulcan's orbit and provided new ephemerides to find it, but the response was always the same: no one (including himself) could observe it. In 1861, there were no reports of observations (professional or amateur) that would confirm the existence of Vulcan. The few reports that were related to the subject later proved to be sunspots. As Vulcan was so near the Sun, it was practically unobservable. This argument was considered reasonable by many observers, mainly those who had suffered damage to their eyes in the attempt of finding Vulcan in the vicinity of the Solar disk.

How to detect a body that is so elusive? Once again, Le Verrier had a solution: Vulcan would be visible during Solar eclipses, when the Solar disk is hidden. Then, he began distributing his new predictions of optimal observation dates. But even so, no one was able to find Vulcan. It seemed evident that Vulcan was a fictional planet, and its existence began to be considered an astronomical myth. Among the astronomers, confidence in Le Verrier's data began to decrease. Yet, Le Verrier could not accept that the astronomical community was unable to detect Vulcan. His position was based on three facts: (1) his role in the epic discovery of Neptune, (2) his absolute confidence in the validity of Newtonian mechanics, and (3) his confidence in the accuracy of his calculations. Le Verrier kept announcing new predictions. But as time passed, fewer and fewer people were paying attention. The scientific community started to doubt everything Le Verrier said about that new world. For several years, he published updated ephemerides (always supposedly definitive), but the planet was nowhere to be found. Finally, Le Verrier died with the certainty of having discovered a planet between Mercury and the Sun, and convinced that it would be detected in the future.

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[48] Le Verrier gave no credit to the testimonies of French astronomer Emmanuel Liais (1826–1900), director of the Rio de Janeiro Observatory. Studying the Sun through a telescope more powerful and sophisticated than Lescarbault's, Liais denied that any planet had transited the Solar disk.

19.2.2.3 A Fictional Reality

After the death of Le Verrier, Simon Newcomb (1835–1909) considered other possible causes to explain the anomalies of Mercury's orbit, as the flattening of the Sun, but the obtained value for Mercury's perihelion shift was not sufficient to explain the 43 arcsec/century. In 1894, Asaph Hall (1829–1907) proposed to alter Newton's law of universal gravitation, adding a term varying as the inverse cube of the distance and a constant adjusted to reproduce Mercury's anomalous perihelion shift.[49] When Newcomb observed similar anomalies on Venus, Earth, Moon, and Mars (although with much lower discrepancies), he realized that Hall's newly proposed law failed to account for them. Although Hall's proposal did not succeed, it opened doors for a new law of gravitation that might be the right answer. In 1906, Hugo von Seeliger (1849–1924) offered a more accurate explanation for the value of Mercury's perihelion shift: a distribution of mass around the Sun, with an inclination to the ecliptic of 7°. Coincidentally, such a mass would also be responsible for the zodiacal light.[50]

It was Albert Einstein (1879–1955) who was able to provide an alternative, successful answer to Mercury's perihelion shift. Einstein's theory predicted that the planetary orbits experienced a slight shift due to the curvature of spacetime. Thus, Einstein's theory seemed to have solved a problem that had troubled astronomers for decades (and ended the illusion of a "Vulcan" between Mercury and the Sun!). Before Einstein, Paul Gerber (1854–1909), German physicist and teacher, provided a formulation for the perihelion shift similar to that of Einstein in 1898. Gerber assumed that gravity is propagated at the speed of light and that the force between two masses should be corrected by a term dependent on the speed at which they move. His formula could explain the anomaly of Mercury, the terrestrial planets, and even the Moon. Gerber's work had little impact because its derivation was quite unclear and, years later, was found to contain some wrong arguments. Einstein always claimed that in 1915 he was unaware of Gerber's work and that had he known it, it would not have influenced the development of his theory.

19.2.2.4 Perspectives

The story of the discovery of Neptune and the Vulcan hypothesis illustrates how personal, cultural, and social considerations drive scientific inquiry. But it also constitutes a telling example of scientific inquiry motivated by observational

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[49] Hall (1894) noted that he could account for Mercury's precession if the law of gravity, instead of falling off as $1/r^2$, falls off as $1/r^n$, with $n = 2.00000016$.

[50] Erwin Freundlich (1885–1964) found that the mass needed to explain the anomaly was incompatible with the mass postulated by Seeliger, given the low luminosity of the Zodiacal Light (1915). Still, Seeliger's hypothesis survived and was one of the arguments of the detractors of Einstein until 1919.

anomalies that, if reliable, demand the revision of our most trusted theories. That similar methods of discovery of new celestial bodies are still in use today only makes this story more pedagogically relevant. In particular, exoplanets are, like Neptune, discovered indirectly, by their induced effects on other, observable bodies, for example: a) using planetary transits to determine the decrease in light intensity of a star when a planet passes in front of its disk or b) using radial velocities to determine the gravitational pull of a planet over a central star.

19.2.3 "Planet," What's in a Name?

19.2.3.1 Is Pluto a Planet? The Evolution of a Scientific Concept

On August 24, 2006, 424 astronomers gathered in a room and decided, with a majority vote, that Pluto would no longer be called a planet. This decision caught the public's attention as it seems to defy not only our common conceptions about our astronomical neighbors but also our understanding of scientific methodology altogether. How can one reconcile rigorous fact-based process with voting? This case illustrates the dynamics of conceptual change and the historical character of scientific theories and concepts. The evolution of the concept of planet illustrates discussions that touch on methodological and ontological issues in science. Learning about the historical evolution of the concept of planet allows one to see how classifications rely on a larger understanding of the world and shape our investigation.

These concerns can be illuminated by philosophical discussions on natural kinds. A kind (property or object) is said to be natural if its existence, behavior, and properties do not depend on humans and are not the product of our decision (e.g., electron, hydrogen, magnetic field…). In contrast, folk kinds are the product of cultural conventions or other idiosyncrasies and may evolve at our will. For instance, continent is seen as a folk kind or cultural – as opposed to natural – object. When geologists refer to continents, they think of "large, continuous, discrete masses of land, ideally separated by expanses of water" (Lewis and Wigen 1997, p. 21). But there is no non-arbitrary way to define what counts as a large mass of land. But, contrary to what happened for planets, geologists did not vote on an official definition for continent and on their number.

19.2.3.2 The International Astronomical Union 2006 Decision

Between 2003 and 2005, Sedna, Eris, Haumea, and Makemake – four distant bodies of the same order of size as Pluto – were discovered beyond Neptune's orbit. This confirmed planetary scientists' suspicion that the confines of the Solar System may contain several other such bodies. Consequently, it became more apparent that it was arbitrary not to count Ceres or Vesta among planets if all these newly discovered Pluto-like bodies were to be counted as such. Based on their equatorial diameters, a category of Solar System objects stands out clearly: the giant planets (Jupiter, Saturn, Uranus, and Neptune), whose diameter is several times greater than Earth's. A second category, that of the terrestrial planets, contains at least several, undisputed planets: Mercury, Venus, Earth, and Mars. But whether or not any or some of the smaller bodies of the Solar System belong to that second category is unclear. Some of them are not much more different from the terrestrial planets than the terrestrial planets are from the giant planets. If Pluto was to be called a planet, then why not Eris, Haumea, or even Vesta? Where should we draw the line? How and why?

To answer these questions, several proposals were made in the years that led to the IAU decision:[51]

1. Alan Stern and Harold Levison (2002) from NASA suggested to define planet in term of *intrinsic properties* of mass: to be called a planet, "the body must: (1) Be low enough in mass that *at no time* (past or present) can it generate energy in its interior due to any self-sustaining nuclear fusion chain reaction (or else it would be a *brown dwarf* or a *star*). And also, (2) Be large enough that its shape becomes determined primarily by gravity (…)" (Stern and Levison 2002, p. 4).
2. Steven Soter (2006) from the American Museum of Natural History, on the other hand, suggested that planet be defined by the *historical process* from which they result, as the end product of secondary accretion from a disk around a star or substar (also known as brown dwarf). That definition allows us to consider the ratio of the mass of a body to the aggregate mass of all the other bodies that share its orbital zone as a good physical criterion, related to the historical formation process of a body, to discriminate planets and non-planets. If not the product of such an accretion, it will only be one of the many planetesimals on its orbit, and this ratio will be very different from that of a planet.[52]

Neither definition seemed entirely satisfying nor received widespread approval among astronomers. The first applies to many more bodies than our familiar eight or nine planets, including of course Pluto, but also our Moon and other satellites of the larger planets, and thus does not address the worry that the number of planets would dramatically increase. The second definition puts an emphasis on contingent relational characteristics (to a neighboring star and the other bodies on its orbit) that may not seem as relevant to characterize a natural object in its essence, even though it would have provided a clear criterion to distinguish between planets (the eight largest bodies that have indeed cleared their orbit) and non-planets (Pluto-like and other smaller bodies) in our Solar System.

After several proposals had been discussed that included these two definitions (or a combination of them), the IAU came to a consensus. The 2006 definition that

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[51] For a much more in-depth examination of these proposals and the philosophical significance of this topic, see Bokulich (forthcoming).

[52] That criterion would, for instance, guarantee that Jupiter is a planet even though it has not "cleared its orbit" of other bodies, since the Trojans (a group of small bodies) share its orbit.

received a majority vote was based on a proposal by Uruguayan astronomer Julio Ángel Fernández:

(1) A planet [1] is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.
(2) A "dwarf planet" is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape [2], (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite.
(3) All other objects [3] orbiting the Sun shall be referred to collectively as "Small Solar System Bodies."

Under this definition, only Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune are planets. Pluto is thus relegated to the status of "dwarf planet," a category for bodies that "look like" planets (they have a round shape as a consequence of their mass) but whose formation history does not make them the main object in their orbit (i.e., which have not "cleared their orbits").[53]

This definition is a conciliatory choice in many ways: it relies on *intrinsic* properties (size, mass, shape), thereby incorporating Stern's and Levison's proposal but also addresses our concern about the increasing number of planets by including two relational components (with the requirement that the orbit be "cleared" and around the Sun). In its formulation, this definition preserves as much as possible our conception of a natural kind as a set of intrinsic properties. It also preserves our common conception of planet, by keeping their number low. However, it can be argued that Soter's approach to defining the notion of planet has been vindicated, insofar as relational, dynamical properties are essential to the IAU definition. Even though it is not phrased that way, this dynamical property makes sense in the context of a model of formation of the Solar System.

Alisa Bokulich (forthcoming) noted that this definition of planet, even though it does not only involve intrinsic properties, does not necessarily make it less of a natural kind. In that, she echoes the work of Richard Boyd (1999), according to whom natural kinds should not necessarily be seen as a list of fixed, intrinsic properties but more as families of properties that are clustered in nature as a result of various underlying homeostatic or causal mechanisms. According to this conception of natural kinds, their properties may also be relational or historical, and their extension may even have vague boundaries, contrary to the more classical conception of natural kind (Bird and Tobin 2010). The resistance to Soter's approach to the definition of planet as not consisting only of intrinsic properties is reminiscent of the debate between philosophers about natural kinds.

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[53] Vesta, a large asteroid whose previously round shape has been altered by collisions, is only a Small Solar System Body (SSSB), even though it shares many physical characteristics with the dwarf planets, and is much closer to them in mass and size than to most other SSSBs.

19.2.3.3 Why Was Pluto Ever Considered a Planet? A Brief History of "Planet"

The concept of planet has been redefined several times, following the progress of discoveries and theories in astronomy. The original denomination of planet was conferred to the few celestial objects easily visible to the naked eye and whose relative position to the other stars varies: Mercury, Venus, Mars, Jupiter, and Saturn.[54] Since then, the number of planets has kept evolving, and so has the meaning of the word "planet." This number kept increasing, as new celestial bodies other than the fixed stars were discovered after the invention of the telescope. The adoption of the Copernican heliocentric model kept the Sun out of the extension of the term. And later, after many moons were discovered, the need for a distinction between planets (which orbit the Sun) and their moons (which orbit their planet) was felt. Similarly, the further discovery of Ceres, Vesta, and other asteroids, but also that of Neptune in 1846, resulted in a distinction between planets and asteroids (smaller than Mercury). Like Neptune, Pluto was discovered as the result of a hunt for a large planet – *planet X* – that would explain perturbations in Uranus's orbit. Thus, the planetary status of Pluto was decided *before* its discovery in 1930 by Clyde Tombaugh (working under the direction of Percival Lowell). It is only after decades of research that scientists came to the realization that Pluto was only one of several relatively small, Pluto-like bodies in the outer Solar System and not the large planet it was once thought to be (see Brown 2010; deGrasse Tyson 2009; Weintraub 2008).

Drawing a parallel with the species problem,[55] Bokulich recalls how philosophical work by Joseph LaPorte (2004) clarifies the options scientists face when their categories (or more specifically taxa in the context of species) are inadequate, too vague or inconsistent. Facing the inadequacy of a taxon,[56] scientists only have limited choices: either expand the taxon, pare it down, or abandon it as a scientific term altogether. By 2006, the vagueness of the term "planet" became so apparent that the IAU felt something had to be done if we were to continue to use it. This organization chose to favor the second option: restrict the extension of "planet". As Bokulich put forth,

> Although which of these three options scientists choose to adopt is largely a matter of convention, what was *not* an option for the scientists was to leave the traditional definition and extension of the term planet intact, while having it remain a scientifically *useful* concept. (Bokulich (forthcoming)

Those who mourn Pluto's lost rank have to accept that this decision was a necessary evil to save the concept of planet as a scientific, useful one.

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[54] Although Uranus (and more rarely Neptune) can at times be visible to the naked eye, it is not nearly as bright as these five planets.

[55] The species problem is the difficulty biologists face when trying to define species in a non-arbitrary way.

[56] A taxon is the name applied to a taxonomic group, i.e., a unit in a formal system of nomenclature. This term is mostly used in biology.

19.2.3.4 Is Planet a Useful Scientific Concept?

Classifications, even if they have a conventional aspect, are useful and fulfill an essential role in science. They are most useful when they correspond to natural classifications, when our taxonomy singles out a well-defined class of properties possessed by objects found in nature (natural kinds). These natural properties and objects are best identified through our laws of nature, and our classifications will evolve as our laws – and more generally our understanding of the world – evolve. For example, the fact that the existence of Ceres and Uranus had been successfully predicted by the Titius-Bode law[57] would have rendered the demotion of Ceres tantamount to the rejection of that law or the demotion of other planets. After discovering that the Titius-Bode law was not valid (it failed to predict Neptune's orbit) and that Ceres was, unlike the other planets, only one of the thousands of small bodies on its orbital region, we could demote Ceres from its planetary status at no scientific cost.

Nowadays, planetary scientists would not make much use of a concept that would not distinguish the more massive objects of the Solar System. All of the planets, as defined by the IAU's 2006 decision, are studied individually and have very diverse bulk compositions and atmospheres. Each has a gravitational influence on its environment much more significant than any dwarf planet or SSSB would have. These smaller objects on the other hand are more significantly approached *statistically*, as members of a large collection of similar objects. They may be further divided into, for example, objects of the asteroid belt and trans-Neptunian Objects (TNOs), among which are Kuiper Belt Objects (KBOs) and Scattered Disk Objects (SDOs).[58] These terms and distinctions are at least as meaningful and useful to astronomers as the notion of planet as defined by the 2006 IAU decision.

On the other hand, the usefulness of the notion of "dwarf planet" is not clear. For astronomers only interested in bodies that have an important influence in the Solar System, it is important to distinguish between the larger eight planets and all the other smaller bodies. For those scientists, the category of *dwarf planet* is of no great use. But for planetary scientists interested in the inner structure of astronomical bodies ("planetary geologists" so to speak), it is important to distinguish between SSSBs and all the larger bodies, large enough to have attained hydrostatic equilibrium. However, the distinction between planets and dwarf planets – or even that between planets and moons – is of no great use. A more likely explanation for the existence of the category of dwarf planet is that it maintained Pluto in a somewhat privileged position among the SSSBs (see Weintraub 2008). One can only speculate what the emotional response of the general public would have been if the planet that gave its name to a beloved Disney character (and the only planet discovered by an American) had lost even the right to be called "dwarf planet"!

The definition adopted by the IAU makes of planet a clearly, empirically identifiable notion, ready to be used in a scientific characterization of our Solar System

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[57] According to the Titius-Bode law, there should be planets at a distance a from the Sun, with $a = 0.4 + 0.3 * 2^m$ for $m = -\infty, 0, 1, 2, \ldots$ (in astronomical unit).

[58] SDOs are objects identified by their orbital characteristics.

according to our best knowledge at hand. In that sense, planet thus defined is a natural object more than a cultural one. The difficulty to come to such a definition depends on our knowledge of the population of the Solar System, but also on what we expect from scientific definitions, namely, to what extent they should capture natural kinds. The IAU could have made other choices, and it is not obvious that the concept of planet is as useful as other subcategories used by planetary scientists, other astronomers, or scientists in general. In any case, such decisions are not binding for scientists. This definition may not be as relevant or clear-cut in the future as the science evolves.[59] This may explain why the 2006 IAU decision was not warmly received within the profession. While 424 astronomers took part in the vote, more than a 1,000 present in the room where the vote was held *did not cast a vote*. Mike Brown, one of the discoverers of Eris and Sedna, agreed with the IAU decision and thinks that the newly adopted definition of planet is *"the best possible scientific definition we could have."*[60] However, he expressed doubt that a definition was even necessary, explaining that the concept of planet could have been left aside by the scientific community and be seen as a cultural rather than scientific concept, akin to that of continent.[61]

19.2.3.5 Interest for Science Education

Planet will be one of the first categories taught in a science class, even at an early age when the notion of the Earth as a planet is not fixed. And yet students' and teachers' misconceptions on the basic structure of the Solar System are common and persistent (Sadler et al. 2010; Frède 2006). Debating the question of the planetary status of Pluto or the relevance of the IAU definition could make for an active, student-centered, and concept-centered way to learn about the structure of the Solar System as well as methodological aspects of scientific taxonomy. Indeed, in order to take part in this debate, one has to have a notion of the Solar System that includes not only the main planets and the Sun but also asteroids and other small bodies. Taking a side implies understanding notions that should be mastered by the end of a secondary-level education.[62] In such a debate, philosophical considerations about the level of arbitrariness and empirical grounding of scientific concepts can help teachers justify what definitions are receivable and why.

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[59] Already its use is being perverted in many articles that refer to planets outside our Solar System, as it seems quite natural to talk about "planet" rather than "exoplanet" when the context is clear.

[60] http://web.gps.caltech.edu/~mbrown/eightplanets/. It is to be noted that he was not present at the 2006 IAU meeting, not being a member of the organization at that time.

[61] Interview on the American National Public Radio (*Science Friday*, August 18, 2006).

[62] Namely, (1) that many bodies other than the largest ones that are visible to the naked eye are part of our Solar System; (2) that these bodies orbit the Sun; (3) that orbits are not necessarily circular and that only certain objects of the Solar System have almost circular orbits, located in the same plane; (4) that some of these bodies are spherical because they have a sufficient mass; and (5) that sufficiently massive bodies "clear their orbit"

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Part VII
Pedagogical Studies: Cosmology

Chapter 20
The Science of the Universe: Cosmology and Science Education

Helge Kragh

20.1 Introduction

Whether majoring in science or not, students at high school and undergraduate university level are confronted with issues of cosmology, a subject which has only attracted a limited amount of attention in the context of science education (Kragh 2011a). It is important that when students are introduced to cosmology, this is done correctly not only in the technical sense but also in a conceptual sense. As shown by several studies, misconceptions abound in both areas. They include some of the philosophical aspects that are so closely intertwined with cosmology in the wider sense and to which a large part of cosmology's popular appeal can be attributed. These aspects need to be addressed and coordinated with the more standard, scientific aspects. In this respect it is often an advantage to refer not only to the modern big bang theory but also to older developments that may illuminate modern problems in cosmology in a simple and instructive manner.

Following a brief discussion of the development of cosmology as a science, the article focuses on various conceptual misunderstandings that are commonly found in students' ideas about modern cosmology. Some of these misconceptions are of a philosophical nature, for example, related to the concept of the universe and its supposed birth in a big bang. By taking issues of this kind seriously, students will hopefully be brought to reflect on the limits of science and adopt a critical attitude to what scientific cosmology can tell us about the universe.

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20.2 Early Cosmology: Lessons for Science Education

According to the view of most physicists and astronomers and also according to some historians of science (Brush 1992), cosmology became a science only in the twentieth century. Some will say that the supposed turn from 'philosophical' to truly scientific cosmology only occurred with the discovery of the cosmic microwave background radiation in 1965, while others date the turn to Edwin Hubble's insight in the late 1920s of the cosmological significance of the galactic redshifts. Others again suggest that the turning point is to be found in Albert Einstein's cosmological model of 1917 based on his general theory of relativity.

The widely held opinion that there was no scientific cosmology – scientific in more or less the modern sense of the term – before Einstein and Hubble entered the stage is reflected in most introductory textbooks in physics and astronomy. The general structure of these books is to start with the solar system and then proceed to stars and galaxies, ending with the universe as a whole. The chapters on cosmology are usually restricted to post-1920 developments (Krauskopf and Beiser 2000). Although earlier developments are sometimes included, then it occurs in sections that appear separate from the account of modern cosmology and are typically placed in the beginning of the book. For example, the epic confrontation between the Aristotelian-Ptolemaic universe and the heliocentric world system during the so-called Copernican revolution is a classic theme in the teaching of physics and astronomy, where it is often presented as a methodological case study. On the other hand, textbooks and similar teaching materials rarely refer to other parts of the rich history of cosmological thought, for which teachers and students must look up the literature written by historians of science (North 1994; Kragh 2007). The exception to this state of affairs is Olbers' famous paradox of the dark night sky, dating from 1826 but with roots back to Johannes Kepler, which can be found in most textbooks.

Although modern cosmology dates in most respects from the early part of the twentieth century, it does not follow that earlier theories about the universe were not scientific. The cosmos of the ancient Greeks was very different from ours, yet Ptolemy's cosmology was basically scientific in so far that it was a mathematical model that rested on observations and had testable consequences. At any rate, there are good reasons to include aspects of pre-Einsteinian cosmology also in the context of science education. For one thing, students should be aware of this earlier development for general cultural reasons. Moreover, the earlier history of cosmology provides many more examples of educational relevance than just the one of the Copernican revolution. Although Michael Crowe's two books on theories of the universe are not ordinary textbooks, they are based on his very extensive experience with teaching history of astronomy and cosmology at the University of Notre Dame (Crowe 1990, 1994). They are of value to the teacher of introductory astronomy courses because they include a large amount of primary sources from Ptolemy to Hubble that can be easily used in the classroom. Moreover, Crowe (1994) includes laboratory exercises related to the studies of the nebulae by William Herschel in the late eighteenth century and by William Parsons, the Earl of Rosse, in the mid nineteenth century.

To illustrate the relevance of earlier cosmological thought in science education, consider the discussion in the thirteenth century concerning the possibility of an eternal yet created universe. The discussion was abstract and philosophical, not scientific, but it is nonetheless of relevance to problems of modern cosmology because it led Thomas Aquinas and other scholastic thinkers to scrutinize the concept of creation in a sophisticated way that went beyond the identification of creation with temporal beginning (Carroll 1998, see also below). As another example one might point to the difficult problem of spatial and material infinity as it turned up in Isaac Newton's correspondence with Richard Bentley in the early 1690s. Both Bentley and Edmund Halley mistakenly believed that in an infinite stellar universe each star would be attracted by equal forces in any direction and therefore be in a state of equilibrium. The belief is intuitively convincing and probably shared by most students, but Newton knew better. As he pointed out, two infinities do not cancel. The case is well suited to discuss with students the tricky problems of infinities that appear no less prominently in modern cosmology than they did in the past.

Students should also be aware that the fundamental distinction between realism and instrumentalism, an important issue in the discussion of the nature of science (Campbell 1998), does not turn up only in microphysics but also in cosmology. After all, the universe is no less unobservable than are quarks and superstrings. No one has ever observed the universe and no one will ever do so, so how can we know that the universe exists? The realist will claim that 'the universe' designates an entity that exists independently of all cosmological enquiry, while the instrumentalist considers it a concept that can be ascribed a meaning only in a pragmatic sense, as it is a construct of cosmological theory. The tension between the two opposite views can be followed through much of the history of cosmology, from Ptolemy's world system to the modern multiverse, and from a teaching point of view, it may sometimes be an advantage to refer to older sources rather than to modern examples. To illustrate cosmological or astronomical antirealism with regard to theories, one may read passages of Stephen Hawking (a positivist and instrumentalist), but the same point is brought home, and with greater clarity, by Andreas Osiander's notorious preface to Nicolaus Copernicus' *De Revolutionibus*.

20.3 Patterns in the Development of Modern Cosmology

To the extent that practicing scientists are familiar with philosophical theories of science, the theories are often limited to the views of Karl Popper and Thomas Kuhn. The ideas of these two philosophers are also likely to be the only ones that students will meet, either explicitly or implicitly, in physics and astronomy courses.

While historians agree that Kuhn's theory of scientific revolutions does not in general fit very well with the actual history of science, the history of cosmology yields some support for the notion of paradigm-governed science and revolutionary changes, if not in the radical sense originally proposed by Kuhn (Kragh 2007, pp. 243–245). In both the older and the modern history, there are several cases of beliefs and traditions that formed the nearly unquestioned framework of cosmological thinking and hence had the character of paradigm. Thus, until about 1910, it was generally believed that the stellar universe was limited to the Milky Way. As the astronomy writer Agnes Clerke asserted, ‘No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way’ (Clerke 1890, p. 368). She added: ‘With the infinite possibilities beyond, science has no concern’.

Likewise, until 1930, the static nature of the universe as a whole was taken for granted. Current cosmology is solidly founded on Einstein’s theory of general relativity and some kind of big bang scenario, elements that are largely beyond discussion and conceived as defining features of cosmological theory. Yet, although it may be tempting to characterize these beliefs as paradigmatic, they are so in a different sense from what Kuhn spoke of in his classical work of 1962, *The Structure of Scientific Revolutions*. First of all, there is no indication of radical incommensurability gaps in the development that led from the static Milky Way universe to the current standard model of big bang cosmology.

The applicability of the Kuhnian model to the case of modern cosmology has been investigated by Copp (1985) from a sociological perspective and by Marx and Bornmann (2010) using bibliometric methods. Marx and Bornmann examine what they misleadingly call ‘the transition from the static view of the universe to the big bang in cosmology’, a process that supposedly occurred in the mid-1960s when the steady state model was abandoned in favour of the hot big bang model. (In reality, the transition from a static to a dynamic universe occurred in the early 1930s and was unrelated to ideas about a big bang.) As indicated by bibliometric data, the emergence of the victorious big bang model in the 1960s marked a drastic change in cosmology, if not a sudden revolution.[1] Based on citation analysis, the two authors suggest that if there were a paradigm shift, it was a slow process ranging from about 1917 to 1965 – which cannot reasonably be called a paradigm shift in Kuhn’s sense.

Shipman (2000) found that nearly half of his sample of astronomers had never heard of Kuhn and that an additional third was only vaguely familiar with him. Of those who were aware of Kuhn’s philosophy, several responded that it informed their teaching and consequently was of value in the classroom. One respondent said: ‘I think changing paradigms are so obvious in astronomical history that it goes almost without saying that his work is interesting to an astronomer, but I never thought to actually make a big deal of it in class’ (Shipman 2000, p. 165). Whereas some astronomers found Kuhn’s model to be helpful in understanding the development of the astronomical sciences, none of them thought it was relevant to their research or had an impact on modern astronomy and cosmology. As one astronomer responded, ‘Kuhn … has no effect on the way science is done’ (p. 169).

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[1] The number of publications on cosmology grew dramatically in the 1960s, apparently an indication of the revolutionary effect caused by the standard big bang theory (Kaiser 2006, p. 447; Marx and Bornmann 2010, p. 543). However, the growth is in some respect illusory, as the number of publications in the physical and astronomical sciences as a whole grew even more rapidly. While cosmology in 1950 made up 0.4 % of the physics research papers, in 1970 the percentage had shrunk to a little less than 0.3 % (Ryan and Shepley 1976). Numerical data can be presented in many ways, sometimes resulting in opposite messages.

In this respect, the case of Popper is rather different as his falsificationist philosophy of science has exerted a strong and documented influence on the astronomical and cosmological sciences and continues to do so (Sovacool 2005; Kragh 2013). Although most cosmologists are only superficially acquainted with Popper's ideas, which they tend to use in a simplified folklore version, they often invoke them as a guide for constructing and evaluating theories. This is evident from the modern controversy over the multiverse, and it was just as evident in the past, when Popperian standards played an important role in the debate between the steady state theory and the class of relativistic evolution theories (Kragh 1996, pp. 244–246). Hawking has in general little respect for philosophy, but in his best-selling *A Brief History of Time*, he nonetheless pays allegiance to the views of Popper:

> Any physical theory is always provisional, in the sense that it is only a hypothesis: you can never prove it. … On the other hand, you can disprove a theory by finding even a single observation that disagrees with the predictions of the theory. As philosopher of science Karl Popper has emphasized, a good theory is characterized by the fact that it makes a number of predictions that could in principle be disproved or falsified by observation (Hawking 1989, p. 11).

Influential as Popperianism as in cosmological circles, the influence is mostly limited to the popular literature and general discussions of a methodological nature. As it is the case with Kuhn, Popper's name very rarely appears in research papers. Perhaps more surprisingly, the same seems to hold for elementary textbooks in astronomy and cosmology. On the other hand, the influence of a philosopher may be visible even though his or her name is missing. Thus, in a brief methodological section, astronomy author Karl Kuhn writes: 'A theory of science must be able to be shown to be wrong. A theory must be testable. Every theory must be regarded as tentative, as being only the best theory we have at present. It must contain within itself its own possibility of destruction' (Kuhn 1998, p. 557). It is then up to the teacher whether Popper should be named or not.

20.4 Conceptions and Misconceptions of Cosmology

Most of the misconceptions about cosmology commonly found among students concern the two fundamental concepts of the expanding universe and the big bang. The two concepts are closely connected, but the precise connection between them is often misconceived.

20.4.1 The Expanding Universe

The standard tradition in introductory astronomy and physics textbooks dealing with cosmology is understandably characterized by an emphasis on observations rather than theory. Observations are used as arguments for new concepts and often presented in a historical context. Expositions typically start with two important and connected observations from the early decades of the twentieth century, Vesto Melvin Slipher's discovery in the 1910s of galactic redshifts and Hubble's conclusion from 1929 of a linear relationship between the redshifts and the distances of the galaxies. Both of these historical cases are easily comprehended and can, moreover, be turned into students' exercises by providing the students with the data used by the two astronomers or by using the students' own data found with a 'simulated telescope' (Marschall et al. 2000). From the Hubble relation, there is but a small step to the expanding universe. Almost without exception, textbooks and popular expositions illustrate the expansion of space by means of the inflating-balloon analogy, which may also be used to introduce the notion of curved space such as applied in relativistic cosmology. This standard and very useful analogy – to 'imagine the nebulæ to be embedded in the surface of a rubber balloon which is being inflated' – was first suggested by Arthur Eddington in (1931), shortly after the expansion of the universe had been recognized (Eddington 1931). It also figured prominently in Fred Hoyle's *The Nature of the Universe* from 1950, a classic in the popular astronomy and cosmology literature.

Although there may be but a small step from the Hubble relation to the expanding universe, the step is real and should not be ignored. Students may be told that the expansion of the universe is an observational fact, but this is not quite the case. We do not *observe* the expansion, which does not follow from the data of either Hubble or later observers. As Hubble was keenly aware of, it takes theoretical assumptions (such that the redshifts are due to a Doppler effect) to translate the measured redshifts into an expansion of the universe. It is quite possible to accept the redshift-distance relation and, at the same time, maintaining that the universe is static, such as many scientists did in the 1930s and a few still do. In fact, Hubble, a cautious empiricist, never concluded that the universe is in a state of expansion. What is 'commonly known' and stated in many textbooks and articles, namely, that 'The expansion of the universe was discovered by Edwin Hubble in 1929' (Lightman and Miller 1989, p. 135), is just wrong. Hubble did not discover the expansion of the universe, and he never claimed that he did (Kragh and Smith 2003).

There is a tendency in textbooks, perhaps understandable from a pedagogical perspective, to simplify and dramatize discoveries. For example, one textbook presents Hubble's discovery of the redshift-distance relation as follows: 'The law was published in a 1929 paper on the expansion of the universe. It sent shock waves through the astronomical community' (Kuhn 1998, p. 512). However, it is only in retrospect that Hubble's paper was about the expansion of the universe, and it did not initially create a stir in either the astronomical or the physical community. According to the *Web of Science*, in the years 1929–1930, it received only three citations in scientific journals.

A much better candidate for the discoverer of the expanding cosmos is the Belgian pioneer cosmologist Georges Lemaître, who in a work of 1927 clearly argued that the universe was expanding and even calculated the quantity that came to be known as the Hubble constant (Holder and Mitton 2012). Contrary to Hubble, Lemaître was fully aware that the measured galactic redshifts are not due to a Doppler effect of galaxies flying through space but must be interpreted as the stretching of standing waves due to the expansion of space, that is, as a relativistic effect. As he explained, if light was emitted when the radius of curvature of the closed universe was R_1 and received when it had increased to R_2, the 'apparent Doppler effect' would be given by $\Delta\lambda/\lambda = R_2/R_1 - 1$. The important difference between the Doppler explanation and the relativistic expanding-space explanation can be illustrated in a simple way by means of the balloon analogy (Lotze 1995). One should distinguish between the expansion of space and the expansion of the material universe, such as most textbooks do. It is much easier to comprehend galaxies moving apart, as were they flying through space, but it is more correct to conceive space as expanding and the galaxies changing their relative positions because of the expansion of space. The counterintuitive notion of an expanding empty space, such as implied by the model first studied by Dutch astronomer Willem de Sitter in 1917, illustrates the difference between the two explanations.

As documented by many studies, the expansion of the universe is not well understood, if understood at all, by either the general public or general science students. Comins (2001) discusses a large number of astronomical and cosmological misconceptions, why they are held and how to correct them.[2] Unfortunately, when it comes to the history of cosmology, he expresses several misconceptions of his own, including that Einstein, because he included the cosmological constant in his 1917 cosmological model, 'missed the opportunity to predict that the universe expands' (p. 162). This common misunderstanding is easily seen to be unfounded, for other reasons because the cosmological constant was part of Lemaître's expanding model of 1927 based on Einstein's equations. Moreover, Einstein did not introduce the cosmological constant to keep his universe from expanding but to keep it from collapsing. In short, a cosmological model may describe an expanding universe whether or not it includes a non-zero cosmological constant.

Asked whether the universe is systematically changing in size or remaining about the same size, nearly 60 % of 1,111 interviewed American adults offered the last response. According to the survey conducted by Lightman and Miller (1989), only 24 % of the respondents said that the universe is expanding. Later large-scale surveys of students following introductory astronomy courses confirm that they have difficulties with the expanding universe and other concepts of modern cosmology. Only a minority of the students revealed a reasonably correct understanding of the meaning of the 'expansion of the universe', and a sizeable minority denied that the universe is increasing in size. Instead they suggested that the phrase was a metaphor for how our knowledge of the universe has increased over time (Wallace et al. 2012). One student answered that the expanding universe is an expression for stars and planets moving away from a central area in the universe, if not necessarily from the Earth (Wallace et al. 2011).

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[2] See also Comins' website on 'Heavenly Errors' that includes nearly 1,700 common misconceptions that students and other people have about astronomy and cosmology. Among them are that the universe has stopped expanding, that there is a centre of the universe and that all galaxies are moving away from the Earth (http://www.umephy.maine.edu/ncomins/).

Another question that often causes confusion is *what* takes part in the expansion. Although the expansion is 'universal', it does not refer to everything. Objects that are held together by other forces than gravity, such as electromagnetic and nuclear forces, remain at a fixed physical size as the universe swells around them. Likewise, objects in which the gravitational force is dominant also resist the expansion: planets, stars and galaxies are bound so strongly by gravitational forces that they are not expanding with the rest of the universe. There is no reason to fear that the distance of the Earth from the Sun will increase because of the cosmic expansion, although worries of this kind are not uncommon (Lightman and Miller 1989). In the survey conducted by Prather and colleagues (2003), 10 % of the students thought that the expansion of the universe has terrestrial consequences, including the separation of the continental plates that is a central part of the geological theory of plate tectonics. Nor is our Local Group of galaxies expanding. The Andromeda Galaxy, for example, is actually approaching the Milky Way, causing a blueshift rather than a redshift. (In 1913, Slipher concluded that the Andromeda Galaxy approached the Sun, only subsequently to realize that it was an exception to the general pattern of galactic redshifts.) On the other hand, on a cosmological scale, all matter is rushing apart from all other matter at a speed described by Hubble's law, $v = Hr$, where H denotes the Hubble parameter or 'constant'. Since the Hubble time $1/H$ is an expression of the age of the universe, H, it is not really a constant but a slowly decreasing quantity.

There are other and more complex ways in which the expansion of the universe can be misconceived, some of them relating to the magical limit of the recession velocity apparently given by the speed of light c (Davis and Lineweaver 2004; Ellis 2007, pp. 1214–1216). Students learn that nothing can move faster than the speed of light, which is a fundamental postulate of the theory of relativity. But according to Hubble's law, the recession velocity keeps increasing with distance, implying that beyond the Hubble distance c/H, the velocity will exceed the speed of light. Can receding galaxies really cross this limit? If they do, will they then become invisible because their redshifts become infinite? In spite of the apparent contradiction with Einstein's postulate, superluminal recession velocities do not violate the theory of relativity. As Lemaître emphasized in 1927, the recession velocity is not caused by motion *through* space but by the expansion *of* space. According to general relativity theory, redshifts do not relate to velocities, as they do in the Doppler description (both classically and in special relativity), and the redshifts of galaxies on the Hubble sphere of radius c/H will not be infinite.

Not only can the universe, or space, expand faster than the speed of light, we can also observe objects that recede from us with speeds greater than this limit. Students may believe that since the universe came into being 13.8 billion years ago, the most distant objects are 13.8 billion light years away, but in that case they think in terms of a static universe. Since distances between faraway galaxies increase while light travels, the observability of galaxies is given by the look-back time, which is the time in the past at which light now being received from a distant object was emitted. As a result of the expansion, the farthest object we can see is currently about 46 billion light years away from us, receding with more than six times the speed of light, even though the universe is only 13.8 billion years old. The size of the observable universe is not given by the Hubble sphere but by the cosmic particle horizon beyond which we cannot receive light or other electromagnetic signals from the galaxies.

20.4.2 The Big Bang

Having digested the notion of expanding space, the next crucial concept that students need to be introduced to, the idea of the big bang, is often presented as a simple consequence of the cosmic expansion.[3] After all, if the distances between galaxies (or rather galactic clusters) increase monotonically, apparently there must have been a time in the past when all galaxies were lumped together. This inference is facilitated by the balloon analogy, where the airless balloon corresponds to the original universe before expansion. However, the inference is more seductive than correct. The argument from expansion to big bang may be pedagogically convincing, but it is not supported by either logic or the history of science. If there were such a necessary connection, how is it that while the majority of astronomers in the 1930s accepted the expansion of the universe, practically no one accepted the idea of an explosive origin?

In the version of the 'primeval atom' hypothesis, the idea of a big bang was first suggested by Lemaître in 1931 – not in his 1927 paper, as is often stated – but it took many years until the hypothesis was taken seriously. The hypothesis was independently revived and much improved by George Gamow and his collaborators in the late 1940s, but even then it failed to win much recognition (Kragh 1996, pp. 135–141). Remarkably, from 1954 to 1963, only a single research paper was published on the big bang theory. During most of the period from about 1930 to 1960, the favoured theory of the evolution of the universe was the Lemaître-Eddington model according to which the universe had evolved asymptotically from a static Einstein state an infinity of time ago. This kind of model is ever expanding but with no big bang and no definite age.

Teachers presumably want their students to accept the big bang theory, but not to do it by faith or authority. To convince students that the big bang really happened, they need to provide good reasons to believe in it, which primarily means observational and other empirical evidence. In this respect, the students may be compared to the majority of astronomers and physicists who still in the 1950s resisted the idea of a big bang, basically because they lacked solid empirical evidence for the hypothesis. As the sceptics pointed out, quite reasonably, if our current universe has evolved from a very small and extremely dense and hot state several billion years ago, there

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[3] The undignified name 'big bang' was coined by Fred Hoyle in a BBC radio programme of 1949, but neither Hoyle nor other scientists used it widely until the late 1960s. Contrary to what is often said (e.g. Marx and Bornmann 2010, p. 454), the phrase did not catch on either among supporters or opponents of the exploding universe. Hoyle belonged to the latter category, and it generally thought that he coined the name as a way of ridiculing the theory, but this is hardly the case. The first scientific paper with 'big bang' in its title appeared only in 1966.

must presumably still be some traces or fossils from it. If no such traces can be found, we have no reason to believe in the big bang and nor is there any possibility of testing the hypothesis.

An additional reason for the cool reception of the big bang theory was that according to most of the models, the calculated age of the universe came out embarrassingly small, much smaller than the age of the stars and smaller than even the age of the Earth, in the 1930s estimated to be about three billion years. A universe that is younger than its constituent parts is of course ruled out for logical reasons. The age problem is mentioned in some astronomy textbooks but not always historically correct. According to Arny (2004, p. 517), the age of Lemaître's primeval-atom universe was 2/3 times the inverse Hubble constant, which at the time, when Hubble's value $H = 500$ km/s/Mpc was generally accepted, corresponded to only 1.2 billion years. The reference should be to the Einstein-de Sitter model of 1932, which assumed a flat space and a zero cosmological constant. Lemaître, on the other hand, assumed a positive cosmological constant by means of which he was able to avoid the age problem and assign to his universe an age of 20 billion years or more.

It is all important that some kind of fossil is left over from the cosmic past, which otherwise would be inaccessible to us and therefore just a postulate one can believe in or not. It would have the same questionable ontological status as other universes in modern multiverse theories. In evidence-based courses in physics and astronomy, students come to understand and accept the big bang picture by means of empirical evidence such as the cosmic microwave radiation and the abundance of helium in the universe. What matters is not so much the right scientific belief as it is to be able to justify these beliefs and distinguish them from ideas that are not adequately supported by evidence (Brickhouse and colleagues 2000, 2002). Students learn that a theory must necessarily be supported by evidence and also that evidence depends on and is only meaningful in relation to the theory in question. The way students learn to accept the big bang corresponds to some extent to the historical situation in the period from about 1948 to 1965.

The celebrated discovery of the cosmic microwave background killed the already weakened rival steady state theory and turned the big bang theory into a successful standard theory of the universe.[4] Although the best known of the cosmic fossils, the microwave background is not the only one and nor was it the most important in the historical development of cosmology. It may be less well known that the distribution of matter in the universe provides us with another and more easily accessible fossil. None of the 219 students questioned by Bailey and associates (2012) referred to the chemical composition of the universe as evidence for the big bang, while 32 mentioned the expansion and three the cosmic microwave background as evidence.

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[4] The classical steady state theory was abandoned half a century ago and for this reason is mainly of historical interest. On the other hand, from a methodological and also an educational point of view, it is an instructive example of how an attractive theory with great predictive power was eventually shot down by new observations. In addition, it illustrates the aesthetic and emotional appeal of a cosmological theory, a phenomenon which is not restricted to the past. While Kuhn (1998, p. 555) covers the essence of the steady state theory, other textbook authors choose to ignore it (Krauskopf and Beiser 2000).

The hypothesis that the distribution of matter reflects the cosmic past was first proposed in the late 1930s, when the first reliable data of the cosmic abundance of chemical elements appeared. The general idea in this line of reasoning is that the nuclear species, or at least some of them, are the products of nuclear processes in the early phase of the universe. This was the guiding philosophy of Gamow and his associates Ralph Alpher and Robert Herman, who in the late 1940s developed it into a research programme sometimes known as 'nuclear archaeology' (Kragh 1996, pp. 122–132). The apt phrase underlines the methodological similarity between this area of physical cosmology and ordinary historical archaeology. It refers to attempts to reconstruct the history of the universe by means of hypothetical cosmic or stellar processes and to test these by the resulting pattern of element abundances. Gamow was unable to account in this way for the heavier elements, but in collaboration with Alpher and Herman, he succeeded in calculating the amount of helium in the universe to about 30 % by weight, in reasonable agreement with observations. This early success of the big bang hypothesis was later much improved and extended to other light isotopes such as deuterium.

What matters is that by the late 1960s there was solid empirical evidence for the hot big bang, primarily in the form of the microwave background and the abundance of helium. This does not amount to a 'proof' of the big bang, but it does provide convincing evidence that makes it rational to accept the big bang picture (which does not imply that it is irrational not to accept it). Alternative cosmological models must, as a minimum, reproduce the empirical successes of the standard big bang model and do it without assumptions of an ad hoc nature. To do so on the basis of non-big bang assumptions turns out to be exceedingly difficult. It was the main reason why the steady state model of the universe was abandoned in the late 1960s. The lack of successful rival models is yet another reason to have confidence in the big bang, if by no means to accept it as true.

Whether students follow an evidence-based approach that corresponds to the historical development or not, it is not enough that they can justify their belief in the big bang picture in terms of evidence for it. They also need to know what this picture is, more exactly. If not the students will believe in the big bang, knowing why they believe it but not knowing what they believe in. Several studies show that students have quite different views of the nature of the origin and evolution of the universe. According to a study of Swedish upper-secondary students of age 18–19 years, they conceive the big bang in a variety of ways:

> For example, there are students saying that the universe has always existed in some way. Others talk about a beginning with the Big Bang, but show that they do not view this as an absolute beginning of the universe. … In addition to the view ascribed above where the Big Bang is viewed as something happening to the whole of the universe, there are also some students who talk about the Big Bang as the origin of the earth and/or the sun (Hansson and Redfors 2006, p. 359).

One of the students described the big bang as an event 'where an explosion made gases and particles spread out in space and then they attracted each other and formed suns' (p. 366). Studies show consistently that the most common misconception of the big bang is to associate it with an explosion of pre-existing matter into empty space (Prather and colleagues 2003; Wallace and colleagues 2012; Bailey and colleagues 2012). Perhaps more surprisingly, only relatively few students connect the big bang to the beginning of the cosmic expansion, and very few think of it as an explosion from nothing.

Although it is hard not to think of the big bang as some kind of explosion of pre-existing matter, it is important to make the students understand that this is at best a somewhat flawed metaphor. Lemaître used the metaphor as early as 1931, when he spoke of his new big bang model as a 'fireworks theory', thereby trying to visualize what happened in the cosmic past. Fireworks explode into the surrounding air, but there is nothing 'outside' that the universe can explode into. While an explosion occurs at some location, the bang of the past did not happen somewhere in the universe. It was the entire universe that 'exploded' and thus the big bang happened everywhere. If this is hard to visualize, it is because it cannot be visualized.

It is also important to be aware that the qualitative meaning of the big bang is that long ago all distances, as given by the scale factor $R(t)$, were nearly zero, after which $R(t)$ increased rapidly. For some 14 billion years ago, the universe was very compact, very hot and, in a sense, very small. The essence of the big bang is not a claim of an absolute beginning in some 'singularity' at $t=0$ but a claim of a state of the universe, much earlier than and very different from the present state, that has evolved into the one we now observe. Another way of putting it is that the presently observed expansion started at some finite time ago in the cosmic past, so that the expanding universe can be ascribed a finite age. Note that this does not necessarily imply that the universe has a finite age. Creation in an absolute and therefore metaphysical sense is not – and fortunately not – a part of the big bang scenario, just as little as an absolute origin of life is a necessary part of the neo-Darwinian evolution scenario.

20.5 The Concept of the Universe

Although cosmology has undoubtedly developed into a proper and impressive physical science since the 1960s, it is not just another branch of physics or astronomy. Nor is it just astrophysics extended from the stars to the universe at large. No, it is a very special and potentially problematic science in which questions of a philosophical (and sometimes religious) nature cannot be clearly separated from scientific questions relating to observation and theory. To present cosmology to students without taking into regard its special nature is to present them with a narrow and distorted picture of the fascinating science of the universe. Questions of a philosophical nature are part and parcel of what cosmology is about, and they should be given due consideration also in educational contexts, if not at the expense of the scientific issues. This is a major reason why modern cosmology, including aspects of its history, should have a prominent role in science teaching and why it enters significantly in many courses for students not majoring in physics or astronomy.

20.5.1 The Cosmological Principle

Much of cosmology's special and potentially problematic nature is independent not only of the big bang but also of the expansion of the universe. Indeed, being basically of a conceptual nature, it is largely independent of modern scientific discoveries. A key problem, no less important today than it was in the time of Aristotle, is simply the unique domain of cosmology, this most peculiar concept of *the universe*. The standard definition of cosmology is something like 'the science of the universe', yet it is far from obvious that such a frightening concept as the universe can be the subject of scientific study. The relatively recent recognition that this can be done, and that even the universe at large is not foreign land to science, is one of the marvels of the modern physical sciences.

Among the epistemic problems that face a science of the universe is that cosmological knowledge seems to be conditioned by certain principles or assumptions that are completely unverifiable and for this reason may appear to be metaphysical rather than physical (Ellis 1984). The best known of these principles is the so-called cosmological principle, namely, the generally held assumption that the universe is homogeneous and isotropic on a very large scale. It is sometimes referred to as the extended Copernican principle, a rather unfortunate name given that Copernicus' universe had the Sun as its fixed and unique centre. First explicitly formulated in 1932, the cosmological principle lies at the heart of all relativistic standard models, but it is not restricted to models governed by the general theory of relativity. Indeed, when British cosmologist Edward Arthur Milne introduced it in 1932, it was in connection with his own theory of the expanding universe which was entirely different from the theory governed by general relativity. The principle assumes that the vast ocean of unobservable regions of the universe is similar to the region we have empirical access to, a region that may well be an infinitesimal part of the entire universe. What is the epistemic status of the cosmological principle? Is it a necessary precondition for cosmology, or is it merely a convenience that may be accepted or not?

The cosmological principle does have an empirical basis in so far that it roughly agrees with observations, but observations can say nothing about the structure of the universe far beyond the Hubble region, not to mention the cosmic horizon. Extrapolations much beyond this scale are necessarily hypothetical as they rest on an assumption of global uniformity that can never be verified. One might also say that they rest on 'faith', although the faith in the global validity of the cosmological principle is supported by local observations and therefore quite different from 'blind faith'. If cosmology rests on an unverifiable and perhaps metaphysical principle, can it still claim to be scientific? This is not to suggest that the cosmological principle is in fact metaphysical but to suggest that it is worth contemplating the status of the principle and to discuss it also in a teaching context rather than merely present it as a reasonable if unprovable assumption (Kuhn 1998, p. 551).

The instinct of many students majoring in science is to react with hostility and distrust to terms such as 'faith' and 'metaphysics'. (For students not majoring in science, see Shipman and colleagues 2002.) Yet, because something is ultimately a matter of faith, it does not imply that it is irrational, unscientific or arbitrary. There is an element of belief in most scientific ideas. It is important to recognize that unverifiability is not a great methodological sin that automatically deprives a theory or field its scientific status. In fact, students are well aware of high-status scientific theories that cannot be verified, although they may never have thought of them as theories that, in a manner of speaking, rest on belief.

Several of our commonly accepted laws of physics can be said to be cosmological in nature in so far that they are claimed to be true all over the universe and in any patch of cosmic space-time. Newton's law of gravitation speaks of the attractive force between any two masses in the universe, and the law of energy conservation is valid for all processes at any time in the universe. They can reasonably be considered statements relating to the universe at large and for this reason implicitly of a cosmological nature. Of course, neither these two laws nor other similar laws can be verified experimentally. The moral is that students have no reason to fear unverifiability in cosmology, since we have to live with this feature anyway. On the other hand, unfalsifiability is a different matter.

Contrary to what some philosophers have argued (Munitz 1986), the cosmological uniformity principle and similar principles are not of an a priori nature, that is, true by necessity. The cosmological principle is a simplifying assumption that could be proved wrong by observation. In that case it would have to be abandoned, but this would not make cosmology impossible, only more complicated. There are plenty of theoretical cosmological models that do not presuppose homogeneity or isotropy. The case exemplifies the important distinction between verifiability and falsifiability that is a central message in Popperian philosophy of science. That global uniformity principles of this kind are indeed falsifiable is further illustrated by the 'perfect cosmological principle' upon which the now defunct steady state theory was based. This principle extended the cosmological principle to the temporal dimension, namely, by claiming that there is no privileged time in the history of the universe any more than there is a privileged position. When the steady state theory was put in the grave in the 1960s, so was the perfect cosmological principle.

20.5.2 The Uniqueness of the Universe

The universe does not only stretch beyond the observable region; it is also, at least according to the ordinary meaning of the term, a unique concept (Ellis 1999). If the universe by definition comprises everything of a physical nature, space and time included, there can only be one universe. Contrary to ordinary physics, which operates with objects and phenomena which are local and of which there are many, the universe is not a member or instance of a class of objects. Newton could establish his inverse-square law of gravitation because there are many bodies that gravitate. By observing and experimenting with different initial conditions, he and later physicists could confirm the validity of the law, but not so with respect to the universe, where the initial conditions are fixed and unchangeable. We cannot rerun the universe with the same or altered conditions to see what would happen if they were different. It seems to follow that we cannot establish proper cosmological laws *of* the universe comparable to the ordinary laws of physics, for we cannot test any such proposed law except in terms of being consistent with a singular ‘object’, the observed universe.

Since we use laws to explain things, such as explaining the falling apple as an instance of the law of gravity or the energy generated by the Sun as an instance of the laws of quantum physics, it may seem that the domain of cosmology is beyond explanation in the causal-nomological sense normally used in physics. To put it differently, whereas in local physics law-governed and contingent properties can be distinguished, this may not be possible in cosmology. Does it follow that the universe – the domain of cosmology – is beyond explanation? The question was discussed by René Descartes and his contemporaries in the seventeenth century, and it has continued to attract attention from both philosophers and cosmologists. According to Descartes, the divine mechanical laws guaranteed that the original chaos, whatever its structure and initial conditions, would evolve into our universe or one indistinguishable from it. Newton, on the other hand, insisted that the universe cannot be fully understood by the laws of mechanics alone. Descartes’ ‘indifference principle’ continues to play a role in modern cosmology, except that the laws are no longer seen as mechanical only (McMullin 1993).

There are ways to avoid the pessimistic conclusion that the universe is beyond explanation. One strategy is simply to deny the uniqueness of the universe by postulating the existence of many others. Another solution is to recall that there are other forms of explanation than those used in the standard deductive-nomological scheme. Because cosmology is a non-nomological science, it does not follow that it is impossible to account for the present state of the universe. Thus, to explain the fact that the present temperature of the microwave background is about 2.7 K, we do not need a law of the universe or an ensemble of universes we can compare ours with. We can and do offer an explanation – not a causal one, but a historical or genetic explanation – by accounting for how the background radiation cooled with the expansion of the universe.

20.6 Unfinished Businesses

Cosmology of the twenty-first century is in some respects an unfinished business that may provide students with a rare insight in science in vivo. Not only are there important scientific questions that are not solved yet, most notably the nature of dark matter and dark energy, there are also questions of old vintage that may belong as much to philosophy as to science and about which we do not even know whether they are answerable or not. Many students are naturally curious about the kind of borderline questions that cosmology present us with, and teachers should do what they can to satisfy their curiosity. Students should be confronted with problems of this kind and be stimulated to think about them in a critical and rational way.

They should not be dissuaded from asking questions even though these may appear to be naïve – maybe they are not so naïve after all. Modern physical cosmology is a wonderful resource for enlightenment and discussion of questions that relate to the limits of science. Contrary to what is the case in most other sciences, such questions are integrated parts of the science of the universe understood broadly. In general science courses dealing with cosmology, it will be natural to introduce at least some of the issues.

20.6.1 Many Universes?

A typical textbook definition is that 'the visible universe is the largest astronomical structure of which we have any knowledge' (Arny 2004, p. 9). This is a reasonable and operational definition, but why restrict cosmology to the study of the visible universe? There surely is something behind it. In the more general and ambitious sense adopted by some cosmologists, the universe is taken to be 'everything that exists'. If so, it makes no sense to speak of other universes. Nonetheless, this is what several theoretical cosmologists do nowadays, where the question of the definition of the universe has been reconsidered as part of the controversy over the 'multiverse', the hypothesis that there is a multitude of different universes of which the one we observe is only a single member (Carr and Ellis 2008; Kragh 2011b, pp. 255–290). This ongoing controversy has many interesting aspects, not least that critics have questioned the scientific nature of the multiverse hypothesis and thus reopened the old question of whether cosmology, or some versions of cosmology, belongs to physics or metaphysics. On the other hand, advocates of the multiverse argue that it is a scientific idea and that it follows from, or is strongly suggested by, recent developments within string theory and inflation cosmology. Although the multiverse cannot be tested directly, they claim that it leads to testable consequences.

The existence of a cosmic horizon beyond which we will never be able to see or otherwise get information from, not even in principle, is not a new insight. As early as (1931), Eddington pointed out that the accelerated expansion of the closed Lemaître-Eddington universe would eventually lead to 'a number of disconnected universes no longer bearing any physical relation to one another' (Eddington 1931, p. 415). This kind of multiverse is relatively innocent, since the different universes, although causally separated, inhabit the same space-time. More extreme and more speculative is the modern idea of a huge number of disparate universes, each of them with its own physical laws, number of space dimensions and constants of nature (and with ours being perhaps the only one with intelligent life). We obviously cannot have empirically based knowledge about the content and properties of these other worlds, nor can we establish their existence observationally. The numerous other worlds may exist or not, but if the question cannot be decided by means of experiment and observation, does it belong to science?

The recent controversy over the universe may well be used in the teaching of introductory cosmology as it does not rely on advanced theories but is essentially of a qualitative and philosophical nature. A recommendable source, most relevant also for the purpose of teaching, can be found in a discussion between George Ellis and Bernard Carr in the journal *Astronomy & Geophysics* (Carr and Ellis 2008). This illuminating source has for some years been used in courses in philosophy of science for undergraduate science students at Aarhus University, and with considerable success. It works very well and provokes much good discussion among the students.

20.6.2 Infinite Space

The problem of the spatial extension of the universe is another of those cosmological questions that have been discussed since Greek antiquity and that we still do not know the answer to. While Einstein's original universe of 1917 was positively curved and with a definite volume, corresponding to a curvature radius of only about ten million light years, the expanding Einstein-de Sitter model of 1932 assumed a flat and therefore infinite space. The same was the case of the steady state universe, where a zero curvature parameter $k = 0$ follows from the perfect cosmological principle. Indirect and model-dependent measurements of the curvature of cosmic space did not lead to a definite answer, but the present consensus model (including inflation and dark energy) strongly favours a flat universe of infinite extent. Assuming the cosmological principle, this implies a universe with an infinite number of objects in it, whether these being electrons or galactic clusters.

Students may tend to think of infinity as just an excessively large number, but (as Newton was well aware of) there is a world of difference between the extremely large and the infinitely large. Actual infinities are notoriously problematic, leading to all kinds of highly bizarre and possibly contradictory consequences. The general attitude of modern cosmologists is to ignore the troublesome philosophical problems of actual infinities and speak of the infinite universe as just an indefinitely large universe, not unlike the students' intuition. Only rarely do they reflect on the weird consequences of the actual infinite – but perhaps they should. Ellis is one of the relatively few cosmologists who take the infinite cosmos seriously, suggesting that the infinities may not be real after all, indeed cannot be real. Ellis and his collaborators argue that physical quantities cannot be truly infinite and that infinite sets of astronomical objects have no place in cosmology. If such quantities formally turn up in a theory or model, it almost certainly means that the theory is wrong. Infinity, they emphasize, 'is not the sort of property that can be physically realized in an entity, an object, or a system, like a definite number can' (Stoeger et al. 2008, p. 17).

Although an infinite universe follows from some cosmological models, we will never know whether the universe is in fact infinite. Observations and theory indicate a flat space, but observations are limited to the visible universe. It is only by assuming the cosmological uniformity principle that we can extrapolate to the universe at large. Moreover, we can never know observationally whether $k = 0$ precisely, only that k varies between the limits $\pm \Delta k$ corresponding to the inevitable observational uncertainties. This observational asymmetry between flat and curved space was pointed out by the Russian mathematician Nikolai Lobachevsky as early as 1829, a century before the expanding universe. It is worth noticing that although the idea of curved space only was adopted by physicists and astronomers with Einstein's general theory of relativity, as a mathematical idea it goes back to the first half of the nineteenth century.

20.6.3 The Enigma of Creation

The traditional version of the big bang theory inevitably invites questions of a philosophical and to some extent religious nature concerning the origin of everything. Although the big bang model is not really a model of absolute beginning or creation, but a cosmic evolutionary scenario, it would be artificial to ignore these questions and simply dismiss them as unscientific. Unscientific they may be, but they are no less natural and fascinating for that. Teachers can keep them out of astronomy and general science courses, but that would be to betray the curiosity and natural instincts of the students. Moreover, questions concerning cosmic creation have a long and glorious history which makes interesting connections between the history of science and the history of ideas, philosophy and religious thought. Whether one likes it or not, the creation of the physical universe is part of the world view of most cultures, and for this reason alone, it should not be ignored in science courses. Fortunately, there is a rich literature on philosophical, political and religious world views and their place in science education (Poole 1995; Matthews 2009).

The problem with creation in a cosmological context is that if we conceive the big bang as an absolute beginning at $t=0$, then a causal scientific explanation of the creation event is impossible. After all, a cause must come before the effect, and there is no 'before'. Current cosmology has traced the history of the universe back in time to the inflationary period which is supposed to have occurred at $t=10^{-34}$ s or thereabout. It is often assumed that the cosmic past can be traced even farther back to the Planck time at $t=10^{-43}$ s (and there are even speculative pre-Planck theories). But however close calculations may bring us to the magical moment $t=0$, it seems in principle impossible to account for the creation event itself. To say that the universe was created in a space-time singularity is a mere play with words, since the singularity is a mathematical abstraction devoid of physical content. Physics did not exist at $t=0$ and it makes no sense to speak of physical mechanisms where even the concepts of cause and effect cannot be defined.

In spite of the rhetoric of some cosmologists, there are no scientific theories that explain the origin of the universe from 'nothing', and there never will be such theories. The concept of nothingness or absolute void has a rich history (Genz 1999) that recently has become relevant to science, not least after the discovery of the dark energy that is generally identified with the vacuum energy density as given by the cosmological constant and interpreted in terms of quantum mechanics. However, the modern quantum vacuum is entirely different from absolute nothingness.

There cannot possibly be a scientific answer to what nothingness is, and yet it does not therefore follow that the concept is meaningless.

A major reason why big bang cosmology has been and to some extent still is controversial in the eyes of the public is that it may be seen as a scientific version of Genesis or at least to provide scientific justification for a divinely created world. This misguided view was endorsed by Pope Pius XII in 1951 (Kragh 1996, pp. 256–259) and is still popular in some circles. Although this is not the place to discuss the complex relations between cosmology and religion (Halvorsen and Kragh 2010), it appears that some of these questions are suited for discussions with and among students and should not necessarily be kept out of the physics classroom. Courses that aim to establish a dialogue between science and religion have existed for some time, and in some of them cosmology enters prominently (Shipman and colleagues 2002). The issue is also mentioned in Kuhn (1998), a textbook which includes a brief and admirably clear exposition of the relationship between cosmology and religious faith:

> If we use God as an explanation for the big bang, there would be no reason to look further for a natural explanation. Use of supernatural explanations would shut down science. … If science relied on a creator to explain the inexplicable, there would be nowhere to go, no way to prove that explanation wrong. The question would have already been settled. … Science does not deny the existence of God. God is simply outside its realm (Kuhn 1998, p. 557).

While much attention is paid to the origin of the universe, the other end of the cosmic time scale is rarely considered a question of great importance. And yet Einstein’s equations of relativistic cosmology are symmetric in time, telling us not only about the distant past but also about the remote future. Will the universe ever come to an end? If so, what kind of end? In the late nineteenth century, these questions were eagerly discussed in relation to the so-called heat death supposedly caused by the increase of entropy in the universe, and recently they have been reconsidered within the framework of modern physics and cosmology. The new subfield known as ‘physical eschatology’ is concerned, among other things, with the final state of life and everything else (Kragh 2011b, pp. 325–353). Parts of physical eschatology are controversial and highly speculative, yet it is a subject that is likely to appeal to many students and that they should know about. As the birth of the universe relates to religious dogmas, so does its death.

20.6.4 A Universe Without a Beginning

In his last book, *The Demon-Haunted World*, the prominent astronomer and science popularizer and educator Carl Sagan pointed out that science might conceivably demonstrate the universe to be infinitely old. He suggested that ‘this is the one conceivable finding of science that could disprove a Creator – because an infinitely old universe would never have been created’ (Sagan 1997, p. 265). On the face of it, Sagan’s assertion may appear convincing, perhaps even self-evident, but it is based on a misunderstanding that conflates the scientific notion of ‘finite age’ with the theological notion of ‘creation’. Theologians and Christian philosophers agree that even an infinitely old universe would have to be created, in the sense of being continuously sustained, and that it would in no way pose problems for faith. Even if the universe had existed in an infinity of time, we could still ask for the reason of its existence or why it was created.

We have very good reason to believe in the big bang, but we have no good reason to believe that this is how the universe ultimately came into being. Concepts such as cosmic origin and time are difficult, not only conceptually but also for semantic reasons. Thus, we would presumably think that whereas the steady state universe of Hoyle and others had always existed, this is not the case with the finite-age big bang universe. The two statements ‘the universe has a finite age’ and ‘the universe has always existed’ appear to be contradictory, but in reality they may both be true. To say that the universe has always existed is to say that it existed whenever time existed. The word ‘always’ is a temporal term that presupposes time. Since it is hard to imagine time without a universe – much harder than imagining a universe without time – it makes sense to speak of a big bang universe which has always existed. The phrase ‘the universe has always existed’ reduces to a tautology. This observation is more than just a philosophical nicety, as illustrated by one of the questions posed to students in a questionnaire: ‘Does the universe have an age, or has it always existed’ (Bailey and associates 2012). Several of the students, we are told, ‘gave a contradictory response, such as “the universe has always existed: it is billions of years old”’. As argued, the answer is not really contradictory.

Until recently, it was taken for granted that a universe of finite age implies an absolute cosmic beginning of some kind. The traditional answer to the supposedly naïve question of what there was before the beginning in the big bang has been to dismiss or ridicule it as an illegitimate and meaningless question. For how can there be something ‘before’ the beginning of time? But there is no reason to ridicule the question if it is recognized that the big bang event at $t=0$ did not necessarily mark the beginning of time.

During the last two decades, an increasing number of cosmologists have argued that the big bang picture does not preclude a past eternity in the form of, for example, one or more earlier universes. Most theories of quantum gravity operate with a non-singular smallest volume, which makes it possible to extend cosmic time through the $t=0$ barrier at least in a formal sense.[5] There exists presently a handful of such theories, which are all speculative to varying degrees but nonetheless are considered serious scientific hypotheses. To mention but one example, according to so-called loop quantum cosmology, the universe was not created a finite time ago but exists eternally. There was a big bang, of course, but in the form of a well-described transition of the universe from a contracting to an expanding phase. The space of loop

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[5] It is far from obvious that the symbol t, as it appears in the equations describing the very early universe near or before the Planck time $t=10^{-43}$ s, can be ascribed a well-defined physical meaning (Rugh and Zinkernagel 2009). The meaning of time is even less clear in theories of quantum cosmology describing the hypothetical universe before $t=0$. The claim that there was a universe ‘before’ ours seems to presuppose a common measure of time in the two universes.

quantum cosmology is discrete on a very small scale (meaning volumes of the order 10^{-100} cm^3), which has the observable consequence that photons of very high energy should travel faster than those of low energy.

Did the universe have an absolute beginning in time or not? The most honest answer is probably that we do not know and perhaps cannot ever know. It may be one of those questions about which we cannot even tell whether it is meaningful or not or whether it belongs to science or not.

20.7 Conclusion

The cosmological world view of the twenty-first century, largely identical to the standard big bang theory, is to a considerable extent what the Copernican world system was in the seventeenth century. Just as this system was not only a new theory of astronomy but also carried with it wider implications related to philosophy, religion and social order, so the modern picture of the universe cannot be easily separated from extra-scientific considerations. Such considerations, be they of a philosophical, conceptual or religious nature, should to some extent appear also in the teaching of science and do it in a qualified and critical manner.

One of the important aims of science education is to bring home the lesson that although science provides us with reliable and privileged knowledge of nature, it does not answer all questions that are worth asking. This lesson emerges with particular force from the study of cosmology. It may be expressed more poetically with a famous quotation from Shakespeare's *Hamlet*: 'There are more things in heaven and Earth, Horatio, than are dreamt of in your philosophy'. Recall that at the time of Shakespeare, the term 'philosophy' had a meaning corresponding to our 'science'.

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Part VIII
Pedagogical Studies: Mathematics

Chapter 21
History of Mathematics in Mathematics Education

Michael N. Fried

21.1 Introduction

On the face of it, with so many good essays on the history of science in science education, a separate chapter on mathematics education might well be thought unnecessary. Considerations regarding history of mathematics in mathematics education, it is true, are similar to those regarding history of science in science education. Similar benefits, for example, have been cited in both cases, including humanizing subject matter, adding variety to teaching, showing alternative approaches to scientific ideas, analyzing students' understandings and misunderstanding, and deepening a sense of the nature of the discipline. For both, too, there are similar difficulties.[1] For one, both must confront mundane but no less worrying problems, such as finding time for history and fitting historical material into an already crowded curriculum; but also they must confront deeper problems arising from the tension between anachronism and relevance and between useful rational reconstruction and faithful historical analysis.

The case of mathematics education, however, differs from that of science education as mathematics itself differs from the natural sciences. That difference, of course, is subtle and cannot be reduced simply to whether one or the other is more empirical or more cumulative. Indeed, it is precisely historical and philosophical studies that have made clear the extent to which science can develop according to nonempirical theoretical issues, while mathematics can take on an empirical or quasi-empirical character, as Lakatos liked to put it (e.g., Lakatos 1986). Still differences do exist along these lines. In arguing his own theory of mathematical

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[1] For a list of some of these difficulties in mathematics education, see Siu (2006).

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change, Kitcher (1984), for example, points out that "…mathematics often resolves threats of competition [between opposing theories] by reinterpretation, thus giving a greater impression of cumulative development than the natural sciences" (p. 159).

Leaving aside whether or not it is justified, this impression that Kitcher refers to, combined with a Platonist tendency to see mathematical objects as given, typically translates into a sense that somehow the mathematics of the past is as valid now as it was in its own time, as opposed to the science of the past, which one easily (often *too* easily) takes to be obsolete or inadequate from the perspective of modern science. Consequently, the historical character of mathematics is often more problematic for students and teachers than the historical character of the natural sciences: it is more difficult, that is, for students and teachers to see mathematics of the past truly *being* of the past, truly different from the mathematics of the present. The benefits and difficulties of incorporating history of mathematics into mathematics education are, in their turn, all colored by this sense of the historical character of the discipline. So, despite striking similarities between questions connected with history of science in science education and history of mathematics in mathematics education, there is good reason to take a closer look at the latter independently of the former. This then is the purpose of the present chapter.

We shall proceed according to the following plan. Part 1 will take a brief look at several early instances of using historical mathematical material for learning. As we shall see, many of the justifications for incorporating history of mathematics in mathematics education proposed today are prefigured in this educational history, and this will give the entire chapter a spiral character. The discussion in this first part will also hint at the question of what it means to have a historical approach in the first place. The reader should be warned, however, that this part in no way presumes to be a thorough history of the subject in any sense of the word; indeed, that history needs one day to be written!

Part 2 will examine three central themes associated with more recent attempts to bring history of mathematics into mathematics education: the motivational theme, the curricular theme, and the cultural theme. Inevitably, these themes, to a greater or lesser degree, rest on presuppositions concerning the nature of mathematics, history of mathematics, and mathematics education itself.

Part 3 then looks more closely at these presuppositions by considering them in light of how historical inquiry in general is understood. It is this part that most directly addresses how the historical character of one's approach in bringing history of mathematics into mathematics education relates to its benefits and difficulties. It asks, at bottom, in what sense do students gain historical *knowledge* of mathematics or an historical outlook regarding mathematics? Tensions between frameworks based on the curricular theme and those based on the cultural theme, in particular, are revealed by this line of thinking. Responding to these tensions may demand reconceiving what mathematics education is about. The use of original sources is examined in this context and is discussed in this part together with some empirical findings.

21.2 Some Early Instances of Using Historical Material in Mathematics Education

In the 1970s, the idea that history of mathematics could play a part in mathematics education began to take root broadly in the mathematics education community. More importantly, in those years, educational interest in history of mathematics became organized at national and international levels, especially, with the establishment of the *International Study Group on the Relations between the History and Pedagogy of Mathematics* (ISGHPM or, as it is now known in its abbreviated form, HPM). The many conferences, books, and international cooperation that arose from the HPM and other organizations tempt one to think that before the 1970s, interest in using the history of mathematics in mathematics education was rare at best, and concrete instances of such use were thin on the ground if existing at all. In fact, historical material has almost always been present, one way or another, in mathematics education, in one form or another.

The qualifications in the last sentence are necessary because of the variety of ways one can treat historical materials and conceive one's relationship to the mathematics of the past and, at the same time, because of the variety of settings for learning mathematics and ways of understanding what it means to be mathematically educated. Notions of what it means to learn mathematics and where mathematics learning takes place are connected to the history of mathematics education proper, which has been an area of active interest on its own in recent years (observe, e.g., the existence of the *International Journal for the History of Mathematics Education* edited by Gert Schubring). But by taking into account the variety of ways of treating history and defining one's relation to the past, the present discussion becomes connected as much, or even more, to historiography. Indeed, although we shall speak of this in more depth later in the third part of this chapter, it is important to keep in mind now that in thinking about how history of mathematics comes into the learning of mathematics, it is impossible to separate considerations of the nature of history itself and of the telling of history from its use in teaching.

The blurred borders between doing and learning mathematics and history and historiography of mathematics are particularly apparent when one tries to understand mathematics education of the ancient classical period. Education in the ancient world is, altogether, a topic difficult to give an account of in plain and simple terms. The key notion is that of *paideia*. This Greek word has been translated variously as "culture," "civilization," "tradition," or, simply, "education"; more tellingly, its typical Latin translation is *humanitas*. The course in *paideia* is the *enkyklios paideia* from which we derive the word "encyclopedia," and yet the acquiring of *paideia* was not considered the acquisition of encyclopedic knowledge. The immense difficulty of the idea of *paideia* is evident in the mere fact that the great classical scholar Werner Jaeger needed three thick volumes to describe it (Jaeger 1945). One can say this though, that *paideia* entailed knowledge of a certain corpus of literature as well as the possession of skills and a presence of mind to think, speak, and act in an intelligent manner, one might say in a *cultured* way.

The emphasis on thinking, speaking, and writing is one reason why rhetorical training was so central in classical education and why some of our best accounts of classical education of the time are specifically of rhetorical education (see, for example, Kennedy 2003). The nature of mathematics education is much less clearly laid out, and there seems to be a large gap between accounts of very elementary education (discussed by Mueller 1991) and the more advanced mathematics education leading to the work of figures like Archimedes and Euclid (Fried and Bernard 2008). One key to understanding classical education, whether it be rhetoric or mathematics, is that such education was pursued for a lifetime; *paideia* had always to be cultivated. The speeches of the fourth century BCE rhetorician, Isocrates, therefore, were explicitly not only speeches as such but also models for himself and his students – production, teaching, and learning, for him, flowed seamlessly into one another.

This makes Marrou's referring to ancient "textbooks" in mathematics, meaning books such as Euclid's *Elements* (Marrou 1982, pp. 177ff) as plausible as it is deceiving. For, on the one hand, even though the *Elements* was used as a school textbook almost into modern times, it was in its own time the work of a mature mathematician addressed to mature mathematical audiences for whom "elements" meant something much more than "elementary" (Fried and Unguru 2001, pp. 58–61). On the other hand, as we noted regarding Isocrates' speeches, the perfecting of one's own *paideia* could include teaching and learning from the *Elements*. In that light, it is quite natural that Proclus, writing both as a philosopher and as the head of the Platonic Academy in the fifth century CE, should produce a commentary on just the first book of the *Elements* and refer often to its effect upon students. And, by the latter, it is perfectly clear Proclus includes himself as well as those younger than him.

Proclus' *Commentary on the First Book of Euclid's Elements* (Morrow 1970; Friedlein 1873) is also one of the important sources we have for the history of mathematics. Proclus refers often to the historical development of mathematics and, by giving his own principal source, Eudemus of Rhodes (fourth century BCE), he also tells us much about one of the early histories of mathematics, Eudemus' no-longer-extant *History of Geometry*. From Proclus, and elsewhere, we know that Eudemus' approach to history involved pointing out and discussing the first discovers of a given result, the *prōtoiheuretai* (see Zhmud 2006). The verb *heurein*, from which we derive the English word *heuristic*, means actually "to find" or "to invent." In the rhetorical educational tradition, *heuresis* is an extremely important term, for while the students, the *manthanontas* (i.e., those who engage in *mathēsis*, learning), learn by imitation, by studying texts, they must simultaneously learn to invent, to engage in *heurēsis* (Kennedy 2003; Fried and Bernard 2008); in rhetoric this means by studying speeches of masters, they learn to invent their own speeches. It is not unreasonable then to assume an educational principle in Proclus' attention to history and in the work of his historian predecessor Eudemus: through learning about the first inventors of mathematical ideas, students discover their own powers to invent. As we shall see shortly, this has remained, *mutatis mutandis*, a motive for introducing historical elements into mathematics education.

It can be argued that although Proclus engages with mathematics and mathematicians of the past, he does not treat these historically. His relationship to earlier mathematicians is one of colleagues, despite the great span of time separating them. But as I have outlined elsewhere, there is a broad spectrum of possible relationships to the mathematics of the past, including that of "colleagues"(Fried 2011, where a sample of eight relationships was described). There are, for example, "treasure hunters," who try and bring up gems lost in the past; "conquerors," like Descartes, who refer to the past to show the superiority of the present; "privileged observers," like H. G. Zeuthen, who think their modern mathematical knowledge privileges them to interpret the past; and "historical historians of mathematics," who view the past as fundamentally different from the present and see the treatment of the past demanding more than present mathematical knowledge. These kinds of relationships do not necessarily correspond to historical periods. For example, regarding "colleagues," even in modern times, Hardy quotes Littlewood as having said the Greek mathematicians were merely "Fellows of another college" (quoted in Hardy 1992, p. 81). Whether or not these relationships are properly historical is just the sort of historiographical question I referred to above and it is far from settled. But one must accept that these relationships are *in some sense* historical; more importantly, they allow us a way of seeing how mathematics of the past, at least in some general way, has entered mathematics teaching and learning.

A "colleague" relationship to mathematics of the past, for example, can be discerned in the use of Euclid's *Elements* and other classic works as texts for teaching geometry from the Middle Ages to the nineteenth century. Howson (1982) points out that in England during the nineteenth century, an enormous number of new editions of Euclid for use in schools were produced and that "Many of these editions were, in fact, Euclid pure and simple; additional notes were often included, but no exercises, for the student was expected to memorise not to act" (p. 131). The study of geometry, in this respect, was identified with the study of a certain historical text. Yet it was not its historical character alone that was behind its use: similar to what I have suggested regarding Proclus, the use of Euclid's *Elements* was justified by its ability to train rigorous logical thinking, as good then as now. Interestingly enough, Howson (1982) makes very clear, the reform of mathematics education in England in the second half of the nineteenth century centered on the rejection of Euclid as a text (see also Carson and Rowlands 2000). It could be said that the whole argument surrounding Euclid's *Elements* stemmed from its being regarded on the same terms as a modern text, that is, as if it were a text written by a colleague. Yet, it cannot be discounted from the present discussion, for one, because there are still proposals for using history of mathematics whose claim to being history comes down to the fact only that a historic text is being used (and the counterargument is often the same as that against Euclid, namely, that it is not modern or not pedagogically sound!). Furthermore, the claim for using Euclid in the mathematics classroom is in line with a common claim for using historical texts in general, namely, that they often present accounts of mathematical ideas that are particularly clear, probing, or challenging.

But more explicitly historical views of the mathematics of the past can also be found in educational materials for teaching mathematics from the same time and before. A relatively early case was the classic 1654 text by the Jesuit Andreas

Tacquet (1612–1660) *Elementageometriaeplanae ac solidae* (Tacquet 1761), originally produced for students studying mathematics in the Jesuit colleges. It opens with a long "historical narrative of the origin and progress of the mathematical sciences" (*historiconarratio de ortu & progressumatheseos*) that students might know to what science the wisest figures of past times had dedicated themselves. In other words, Tacquet was telling his students, in effect, that in order to understand its importance, their study of mathematics must be pursued against the background of its history. He was not the first to hold this position; he himself refers to Ramus (1515–1572) as preceding him in this regard.

In a more formal way, and somewhat closer to the way we imagine history of mathematics entering education, we find in the late eighteenth century, in Poland, a very early interest in history of mathematics as a component of mathematics education – earlier, in fact, than a professional interest in history of mathematics in Poland. Domoradski and Pwlikowska-Brożek (2002) tell us that "The first Ministry of Education in Europe – *Komisja Edukacji Narodowej* (Commission on National Education) (1773–1794) – hoping to improve and broaden mathematics knowledge, recommended that students be acquainted with the history of mathematics beginning from antiquity" (p. 199). The case of Poland is remarkable when one considers that something like national curricula for education were almost nonexistent before the eighteenth century, so that history of mathematics, here, came into the mathematics curriculum almost at the same time the mathematics curriculum, in the modern sense of the word, itself was coming into being.

As for the next century, especially towards its end, one finds clear instances of an interest in the history of mathematics and science in education in French education and educational policy. From around 1869, for instance, questions concerning "the historical method" in science and mathematics began to appear in official "agrégation" examination for teachers of science (Hulin 2005). Somewhat later, Paul Tannery (1843–1904), who falls somewhere between what I called above the "privileged observer" type and the "historical historian of mathematics," developed a course of studies for the history of science to make clear "the order of ideas, true or false, that dominate each of the sciences" (Hulin 2005, p. 393, my translation), and he taught a course in the history of mathematics in the Paris Faculty of Science from 1884 to1886 (Hulin 2005; Peiffer 2002).

An interest in the role of history of science generally continued into the twentieth century in France, culminating perhaps in the activities of IREM (Institut de Recherche sur l'Enseignement des Mathematiques) at the end of the century. But at the start of the century, we have Ernest Lebon, then minister of public instruction, expressing the desire that history of science be made part of secondary school teaching and a sanctioned part of the baccalaureate examination (Hulin p. 389).[2] This interest took in mathematics as well, though at times the justifications for history of science were different than those for mathematics. The physicist Paul Langevin, for example, in the first quarter of the twentieth century was a strong advocate for history of science as a way for combating dogmatism

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[2] Lebon's remarks were made as a delegate to the Congrès' histoire comparée in 1900.

(Bensaude-Vincent 2009, p. 16), which was not a common theme if at all for history of mathematics in mathematics education.

Significant efforts were made to introduce history of mathematics into mathematics education and teacher education in the United States, where ironically, as Robert Hughes has remarked, "Americans love to invoke the idea of American newness" (Hughes 1997).[3] In the period between the last years of the nineteenth and the first quarter of the twentieth centuries, two figures stand out in this and other aspects of American mathematics education. These are Florian Cajori (1859–1930) and David Eugene Smith (1860–1944).

D. E. Smith was an excellent historian of mathematics, but he also made great contributions to mathematics education in America and on the International scene.[4] That history of mathematics, in his view, was not separate from mathematics education is clear from his classic book, *The Teaching of Elementary Mathematics* (Smith 1904), which contains three entirely historical chapters and several others in which history has a part. And at the Michigan State Normal School in Ypsilanti, where D. E. Smith held the mathematics chair, he designed a course on the history of mathematics for teachers that "…became the foremost distinguishing characteristic of Smith's program: the importance of a historical perspective" (Donoghue 2006, p. 562). It is no surprise then that Smith was on the committee that prepared the 1923 report by the *National Committee on Mathematical Requirements* written under the auspices of the *Mathematical Association of America* in which cultural aims of mathematical education, in general, were highlighted, including "…the role that mathematics and abstract thinking, in general, have played in the development of civilization" (in Bidwell and Clason 1970, p. 394).[5]

Looking back across the ocean for a minute, I should mention that the cultural motive described in the 1923 report was also evident in Felix Klein's enthusiasm for a historical component in mathematics education. Historical sections appear in parts I and II of his *Elementary Mathematics from an Advanced Standpoint* (Klein 1908/1939). In the geometry part (part II), Klein states quite explicitly that "…I shall draw attention, more than is usually done…to the *historical development of the science*, to the accomplishments of its great pioneers. I hope, by discussions

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[3] In the same place just cited (Hughes 1997), Hughes, whose focus is art in America, also refers to an American "worship of origins": the tension between old and new seems to be very much part of the American psyche.

[4] It was Smith who suggested the formation of an international society for mathematics education in a paper in 1905 published in *L'Enseignement Mathématique*. This became the *International Commission on Mathematics Instruction*, the ICMI established in Rome in 1908.

[5] Bidwell and Clason correctly point out (p. 394, note 3) that the ideas in this section of the report parallel closely views in other writings by Smith, for example, his "Religio Matematici" published in the *American Mathematical Monthly* (vol. 28, pp. 339–349) in 1921. The latter, I should say, is not strictly speaking about history of mathematics per se; it is piece written on the model of Thomas Browne's *Religio Medici* and tells what the belief is of a mathematician. Nevertheless, one of the articles of faith is that "Mathematics is a vast storehouse of the discoveries of the human intellect. We cannot afford to discard this material" meant to parallel to the claim that "Religion is a vast storehouse of the discoveries of the human spirit. We cannot afford to discard this material" (Smith 1921, p. 348).

of this sort, to further, as I like to say, your general *mathematical culture*: alongside of knowledge of details, as these are supplied by the special lectures, there should be a grasp of subject-matter and of historical relationship [emphases in the original]" (Klein 1908/1939, II, p. 2). Incidentally, this work by Klein was published in the same year as the founding of *International Commission on Mathematics Instruction* (ICMI), initiated by Smith and headed by Klein as its first president. But let us return to America and Florian Cajori.

Cajori's first historical work was published by the US Bureau of Education and was entitled *The Teaching and History of Mathematics* (1890). As Dauben (2002) points out, "…Cajori was the first in a continuing American tradition of mathematicians interested in the history of mathematics due to its perceived value in teaching" (p. 265). Three years later, Cajori wrote a textbook for the history of mathematics, underlining his interest that this be used by students, rather than other mathematicians or professional historians of mathematics. Cajori's next book *A History of Elementary Mathematics with Hints on Methods of Teaching* (1896) makes the educational motive for his endeavors into the history of mathematics even more explicit. He opens the preface with a quotation from Herbert Spencer in which the following principle is stated: "The education of the child must accord both in mode and arrangement with the education of mankind as considered historically; or, in other words, the genesis of knowledge in the individual must follow the same course as the genesis of knowledge in the race".[6] Cajori then uses this to justify his own use of history of mathematics for mathematics teaching:

> If this principle, held also by Pestalozzi and Froebel, be correct, then it would seem as if the knowledge of the history of a science must be an effectual aid in teaching that science. Be this doctrine true or false, certainly the experience of many instructors establishes the importance of mathematical history in teaching. (p. v)

It is interesting to note that these works of Cajori were carried out before he carried out serious historical work on mathematics under the instigation of no less than Moritz Cantor. (Dauben 2002, p. 266) In other words, Cajori's interests in history of mathematics, as an independent field of inquiry, came *after* his interests in it as an adjunct to teaching.

The principle adduced by Cajori to justify his own historical approach is one of the most persistent and in some ways the most serious reasons given for using history of mathematics in mathematics education. The principle is called variously the genetic principle, the biogenetic law, the principle of parallelism, or the recapitulation principle, after the famous biological principle associated with Ernst Haeckel (1834–1919) that ontogeny, the development of an individual, recapitulates the development of the species, phylogeny (see Schubring 2011; Furinghetti and

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[6] Cajori continues the quotation in which Spencer attributes this principle to Auguste Comte insisting at the same time that the principle can be accepted without accepting Comte's entire theory of knowledge. That Cajori leaves this in the quotation may be a sign that he too had reservations about Comte's theories taken as a whole. Still he, like Spencer, accepts the general genetic principle as a principle for guiding education. The quotation is from the second chapter, "Intellectual Education," of Spencer's *Education: Intellectual, Moral, and Physical* first published in 1861 (Spencer 1949/1861).

Radford 2008).[7] Important figures in the early development of modern mathematics education were adherents to the principle. Thus, calling on the biological principle as his model, Poincaré wrote in 1899 in, that "The educators' task is to make children follow the path that was followed by their fathers, passing quickly through certain stages without eliminating any of them. In this way, the history of science has to be our guide" (*L'Enseignement Mathématique,* quoted in Furinghetti and Radford 2008, p. 633). Felix Klein too, as Schubring (2011) points out, "decisively promoted the genetic principle" (p. 82), even though Klein, as described above, also saw studying history of mathematics in conjunction with mathematics as a matter of general mathematical culture.

The strength of the principle as a guiding principle for mathematics education can be judged by the fact that in 1908[8] an entire book on mathematics education – one of the very earliest books entirely dedicated to the subject – was published by Benchara Branford (1867–1944) in which the genetic principle played a central role.[9] In fact the frontispiece of Branford's *A Study of Mathematical Education* (Branford 1908, see the Fig. 21.1 below) is a "Diagram of the Development of Mathematical Experience in the Race and in the Individual": it is graphic representation of the entire theory, with stages of human history and various occupations such as geodesy and physics as well as what Branford calls primary and derivative occupations (such as miner, shepherd, and scribe, among others, corresponding to "infancy") listed along the left margin; the development of mathematical subjects together with an indication of the degree of "sense activity" and "thought activity" in the center; and the periods of an individual's life – embryonic (!), infancy, childhood, school, college – listed in the right margin. Referring to the diagram, Branford summarizes the educational implication, saying, "Thus, for each age of the individual life infancy, childhood, school, college may be selected from the racial history [i.e. history of the human race] the most appropriate form in which mathematical experience can be assimilated" (p. 245). It is worth noting that later in the work (p. 326), Branford cites exactly the same passage from Herbert Spencer's *Education* quoted by Cajori.

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[7] Although those who use these various terms may see some shades of difference between them, here we shall commit the minor sin of lumping them together into a single perspective, one asserting that historical development can *in some way* provide a guide for individual intellectual development or course of learning.

[8] According to Scott (2009), Branford began the work in 1896.

[9] Schubring (2011) denies that Branford should be taken as the "classical advocate and propagator of that parallelism [the biogenetic principle grafted onto psychology] for the purposes of education" (p. 83). Yet, the fact that Branford took the genetic principle as a guide to his thinking about mathematics education and a "scientific" principle to ground research is certainly clear, and Schubring himself points out that "The merit of Branford's book…lies in his reflections and differentiations concerning the notion of the biogenetic law" (p. 83). Moreover, although Schubring says that too much weight has been placed on the frontispiece of the book, one must consider that that diagram was nevertheless chosen *as* the frontispiece and, therefore, meant to set the stage for the book. Furthermore, it is not merely an illustration presented and forgotten: an entire chapter is dedicated to the interpretation of the figure (Chap. 16), and many of the other chapters follow its structure.

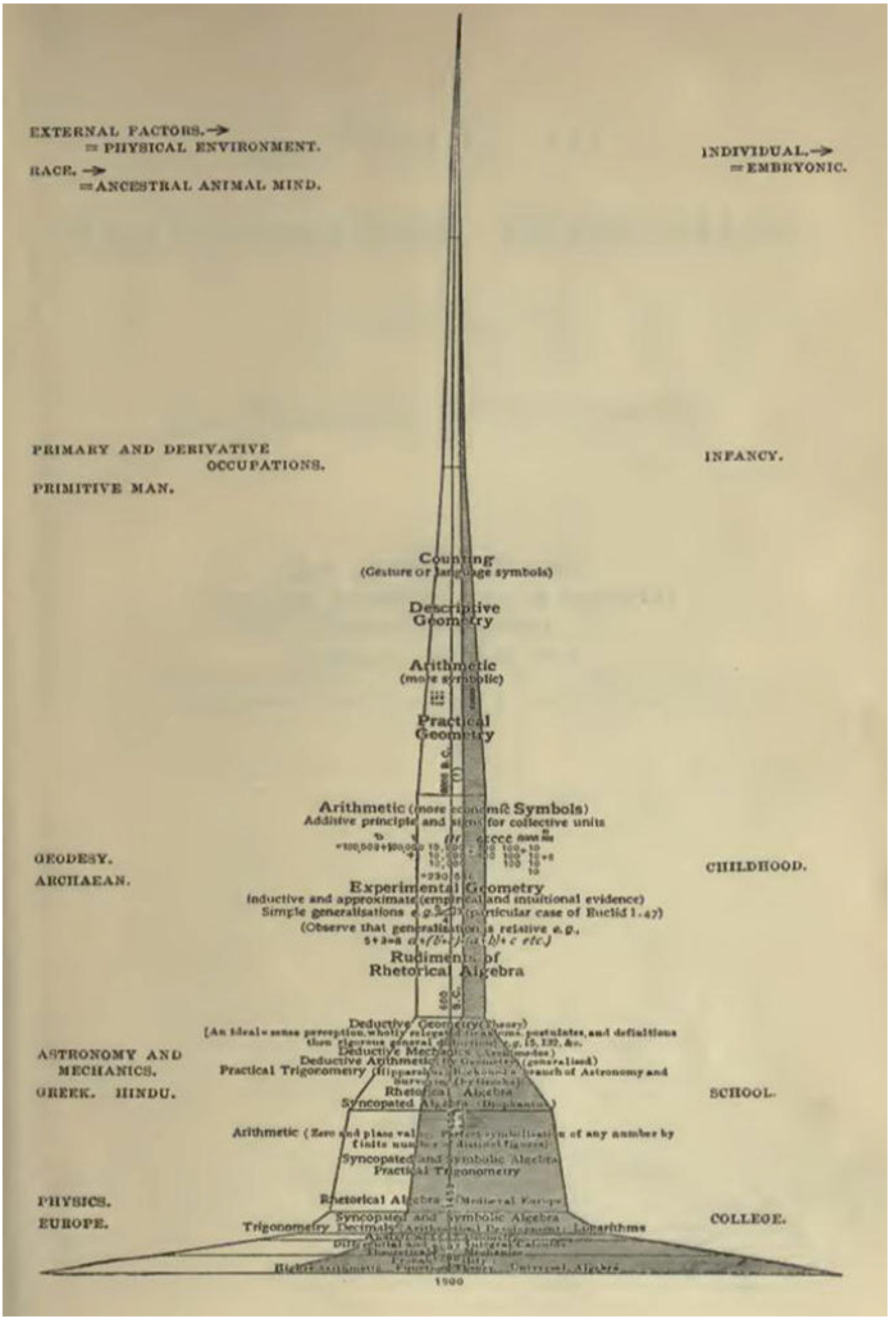

Fig. 21.1 Frontispiece of Benchara Branford’s *A Study of Mathematical Education*

Probably the most famous instance of the genetic approach taken up practically was Otto Toeplitz's (1881–1940) course in calculus according to the genetic methodology, published posthumously in 1949 as *Die Entwicklung der Infinitesimalrechnung: Eine Einleitung in die Infinitesimalrechnung nach der genetischen Methode* republished in English in 1963 as *The Calculus: A Genetic Approach* (Toeplitz 1963). Toeplitz distinguishes between the direct and indirect genetic approach (Toeplitz 1927). In the direct genetic approach, the historical development is presented to the student as a way of presenting mathematical concepts themselves – an approach that should have an effect because of the basic assumption of the genetic principle. It is this direct approach that most characterizes Toeplitz's 1949 work. Thus, he begins his text with a chapter, "The nature of the infinite process," and continues according to the following sequence: "The beginning of Greek speculation on infinitesimals," "the Greek theory of proportions," "the exhaustion method of the Greeks," "the modern number concept," "Archimedes' measurements of the circle and the sine tables," "the infinite geometric series," "continuous compound interest," "periodic decimal fractions," "convergence and limit," and "infinite series." Overall, like most calculus textbooks, he aims towards the idea of limit, but his path to that concept is guided by historical precedents and examples rather than strictly logical considerations.[10]

In the indirect approach teachers use the historical development to draw conclusions about teaching mathematical concepts, which subsequently need not be historical. As Toeplitz puts it, the indirect approach consists of a "Clarification of didactic difficulties, I should say, didactical diagnosis and therapy (didaktische Diagnose und Therapie) on the basis of a historical analysis…" (Toeplitz 1927, p. 99, my translation). About this, Schubring (2011) says "Toeplitz's indirect approach looks not so much on knowledge, but on meta-knowledge, and his main focus is on how to provide future teachers in their training with such a meta-knowledge about mathematics" (p. 9). But Schubring also says that Toeplitz could never really free himself from a teleological viewpoint, from the notion that mathematical development is continuous and cumulative so that "his own notion of an indirect approach could not become fruitful" (p. 10).

Yet, that "teleological" viewpoint seems almost unavoidable if one adopts the genetic point of view. To assume that an individual's mathematical development follows the historical development of mathematics means that the historical development is somehow as natural and directed as that of an organism. It is thus not surprising that in his biography of Toeplitz in the *Dictionary of Scientific Biography*, Abraham Robinson should point out that Toeplitz "…held that only a mathematician of stature is qualified to be a historian of mathematics" (Robinson 2008, p. 428). The genetic point of view suggests a position towards the past that I categorized above as that of a "privileged observer."

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[10] One only has to think of Edmund Landau's famous calculus text (Landau 1965) to grasp the contrast.

21.3 Three Themes in Our Own Time

In these older instances of using history or adopting a historical orientation in mathematics education, one can see the presence and emergence of themes still at work in current discussions of the subject.[11] History of mathematics as part of students' cultural education, a theme recognizing the enterprise of mathematical inquiry as part of students' cultural heritage in general as well as in the specific context of the sciences, has become all the more important as we recognize the centrality and formative power of culture altogether. And it ought to be emphasized here that in recognizing mathematics as a part of culture, one also adopts a view of the nature of mathematics. Let us call this, then, the *cultural theme*, keeping in mind that it is both a reflection on general culture as including mathematics and also on mathematics as being cultural. Besides this theme, which we saw in connection with Felix Klein and D. E. Smith, we also noted the suggestion that history of mathematics can help clarify or deepen the understanding of mathematical ideas: this theme, which could already be found in Proclus and certainly in Toeplitz, continues to be a potent reason for turning to the history of mathematics in mathematics education. Let us call it the *curricular theme*: it includes then both arguments claiming historical treatments of mathematical topics, such as that of Euclid, have great pedagogical power either in themselves or by offering a contrast to modern approaches, as well as the genetic argument and its variations. A third theme, which we did not encounter in our brief survey above, is what we should call the *motivational theme*.[12] We shall begin with this last.

21.3.1 The Motivational Theme

The motivational theme is that history of mathematics makes mathematics teaching less threatening, more human, less formal, and more interesting; the motivational theme introduces an affective consideration into the question of history of mathematics in mathematics education. Ironically, the objection to Euclid in the nineteenth century was partly on the grounds that it was dull![13] In a well-known

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[11] Besides discussions in the context of meetings connected with the HPM mentioned above, other recent forums include those at the CERME meetings. See, for example, Kjeldsen (2011) and Tzanakis and Thomaidis (2012).

[12] Another theme one might suggest is an epistemological theme concerning the possibility that knowing the history of mathematics is knowing mathematics: but this is included in both the cultural and curricular themes together.

[13] That Euclid should be made more colorful was taken up literally by Oliver Byrne who produced a version of Euclid using a system of colors in place of Euclid's lettered diagrams and corresponding text. The book was meant to make Euclid more approachable, as advertized in the full title: *The first six books of the Elements of Euclid in which coloured diagrams and symbols are used instead of letters for the greater ease of learners* (Byrne 1847).

textbook meant to reform the teaching of geometry by replacing Euclid, the author James M. Wilson wrote that:

> We put a boy down to his Euclid; and he reasons for the first time…but we make him reason in iron fetters…we make the study of Geometry unnecessarily stiff, obscure, tedious and barren….And the result is, as everyone knows, that boys may have worked at Euclid for years, and may yet know next to nothing of Geometry (Wilson 1868, pp. vi–vii)

But today, the motivational theme is quite often called upon to justify a historical approach (see Gulikers and Blom 2001, who also refer to "motivational arguments" for history of mathematics). This was certainly the case with Perkins (1991), who saw history as a vehicle for making classroom teaching more interesting and, in so doing, a vehicle for improving students' achievement. A more recent example comes from a Turkish study (Kaygin et al. 2011) in which the authors say, "Thanks to the vast culture and wide knowledge held within the history of mathematics, it becomes easier to understand the abstract concepts of mathematics which is thus [no] longer a subject arousing fear and concern" (p. 961).

A clear statement of the motivational theme can be found in a paper by Po-HungLiu (2003) addressed to teachers and asking, "Do teachers need to incorporate the history of mathematics in their teaching?" Liu's answers include in fact all three of the themes that I have mentioned, but he begins with the motivational theme. He writes:

> As sometimes taught, mathematics has a reputation as a "dull drill" subject, and relevant studies report a steady decline in students' attitudes toward the subject through high school. The idea of eliciting students' interest and developing positive attitudes toward learning mathematics by using history has drawn considerable attention. Many mathematics education researchers and mathematics teachers believe that mathematics can be made more interesting by revealing mathematicians' personalities and that historical problems may awaken and maintain interest in the subject (p. 416)

Pursuing this theme sometimes reduces to light storytelling as in Lightner's "Mathematicians are human too" (Lightner 2000), where Lightner tells a series of humorous anecdotes about mathematicians so that students learn that "…mathematicians were all human beings with peculiar foibles and personality quirks just like the rest of us" (p. 699). For example, Lightner tells us how Norbert Wiener was so absentminded he habitually forgot not only where he parked his car but also which car he drove, and so, after a seminar, he would wait patiently until every car left the parking lot but one, his![14]

As a justification in mathematics education, one should not be completely dismissive of the motivational theme. Getting students to want to learn mathematics is a natural and important goal for mathematics educators, especially when so much emotional baggage truly gets in the way of students' learning mathematics – ranging from distaste and a sense of mathematics as dry and rigid, to frustration and fear.

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[14] Theodore Eisenberg has asked elsewhere (Eisenberg 2008) whether we also ought to tell some of the less amusing stories about mathematicians, about their occasional racism and association with Nazis.

So it is not for nothing that much serious research in mathematics education has looked at affect and its relation to mathematics learning and achievement (e.g. Goldin 2009; McLeod 1994). However, while the educational motive behind the motivational theme may be serious, as a theme connected with the incorporation of history into mathematics education, it is problematic. First, it supposes, not always consciously, that mathematical content alone, unembellished with stories, anecdotes, or colorful characters, cannot itself be made sufficiently interesting to hold students' attention. History is presented as something *to add* to mathematics lessons to "enliven" teaching, teaching that, one must assume, would *otherwise* be dull and dry. Second, history as a body of knowledge to learn and to take seriously is put aside and turned into a mere ploy for drawing students into learning the mathematics their teachers are required to teach. Put baldly, if a good story will keep students from falling asleep in class, tell it; whether or not the story is true, informative, or deep is pertinent, but it is secondary to its being entertaining. And like the story about Norbert Wiener, it does not even have to be, strictly speaking, about mathematics. The motivational theme, accordingly, ends up doing justice neither to history nor to mathematics itself. That said, it must be underlined that similar difficulties exist, albeit more subtly, in other cases where history is brought into the mathematics classroom. The main problem is that history in such cases is superadded to mathematics education, with the particular identity of history as a form of knowledge being lost in the process.

21.3.2 The Curricular Theme

The curricular theme as a focus for introducing history of mathematics into mathematics education must be taken much more seriously, for there is a genuine attempt in this case to see mathematical *ideas* in the light of history. For this reason, it is right that Gulikers and Blom (2001), in their survey of recent literature on history in geometrical education, refer to what I am calling the "curricular theme" as the category of "conceptual arguments." Yet it must be kept in mind that whatever concepts are spoken of here, they are not so much drawn out from the history, but – like the concepts of function, number, and equation – are given in advance, as if from a set curriculum and, only subsequently, discussed historically.

It is in the curricular theme, then, that one sees most clearly the tendency described in my introduction, namely, the tendency to treat the mathematics of the past, though perhaps incomplete, to be as valid now as in its own time. So, for example, even if Euclid did not have group theoretical tools for geometry, he did have theorems on congruence and similarity – and, to that extent, we can use Euclid's work as a basis for our own teaching. Or, in this view, we can take ideas that, from a modern standpoint, are "implicit" in historic texts and translate them into a modern idiom, for example, translating Apollonius' principal properties for conic sections – what he called their *symptōmata* – into equations for conic sections. History of mathematics from the perspective of the curricular theme, as the name implies, makes the least demands from the point of view of the curriculum, for historical treatments of mathematics can be adapted in such a way that they are consistent with a modern program of studies. It is not surprising then that when one looks at Gulikers and Blom's tables of articles in various subject categories of geometry that of the 36 articles in which resources are cited, 24 either have a "written guide with modern exercises," or a "written guide with 'old' problems translated into modern mathematical language" (Gulikers and Blom 2001, Appendix A).

I might point out that this theme could be interpreted as a motivational theme, but in the deeper sense of motivating an idea or a position, an answer to the question, why should we study subject X in chapter Y of the curriculum? This is Fauvel's approach when he discusses the history of logarithms (Fauvel 1995): the paper attempts to provide an answer to a friend who, when hearing Fauvel was thinking about how to teach logarithms, asks "Whatever for?" (p. 39). Fauvel goes on to show in the paper that by considering the history of logarithms, one sees how considerations of this tool, which may be used little nowadays, lead one to important mathematical ideas[15] and ideas about mathematics. The curricular theme, in this light, provides a different nexus for mathematical ideas than would a "logical" approach[16]: providing a motivation for a mathematical idea shows in a way different from pure logic why one idea follows another.

Often the curricular theme is pursued by just taking a problem from the past that allows students to exercise and develop mathematical thinking and skills relevant to their school studies. For example, Kronfellner (2000) uses the problem of duplicating the cube[17] as a means to study topics such as irrational numbers, series, nonlinear analytical geometry, and curves – and he says explicitly that this is one strategy for introducing history into mathematics teaching, namely, "…to offer suitable tasks in which a traditional curriculum topic is connected with history." Swetz's (1995) "Historical Example of Mathematical Modeling: the Trajectory of a Cannonball" is another good instance where a historical problem becomes an opportunity to use and deepen mathematics studied in the classroom. As Swetz puts it: "Contemporary secondary school students can explore a variety of problem-solving situations involving trajectories and use their knowledge of geometry, algebra, trigonometry, vectors, calculus and even computer programming" (p. 101).

In a recent special issue of *Mathematics in School*, Elizabeth Boag's article on the "Dandelin Spheres" (Boag 2010) is a good example of how a historical topic can suggest not just a problem but also an approach to a school subject, in this

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[15] Toeplitz similarly saw the logarithm as an entrance to important mathematical ideas and discusses it prominently in the chapter of his genetic approach concerning the fundamental theorem of the calculus (Toeplitz 1963, Chap. III).

[16] We shall soon encounter the "logical approach" again in connection with the 1962 Memorandum by Morris Kline and associates (Memorandum 1962).

[17] The classic problem is to find the side of a cube whose volume is twice that of a given one. The ancient interpretation was to find two mean proportionals between a line and its double, that is, two lines A and B satisfying the proportion: M:A::A:B::B:2 M. The modern translation is to construct the cube root of 2.

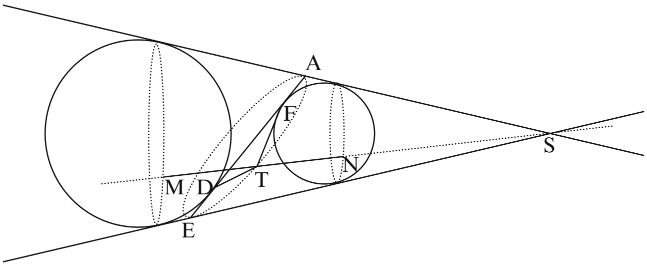

Fig. 21.2 Dandelin spheres for the case of the ellipse

case, the focal properties of conic sections. Just to remind the reader, what G. P Dandelin (1794–1847) showed in the course of his work, "Mémoire sur quelques propriétés remarquables de la focale parabolique"(Dandelin 1822), was that the focal properties of the conic sections, say of the ellipse, could be conceived strictly in terms of the cone. Consider the property that the sum of the lines from a point on an ellipse to the foci is constant: suppose a right cone is cut by a plane such as that containing the line AE and let two spheres be inserted in the cone, tangent to generating lines of the cone and to the cutting plane.[18] As for the latter, let them be tangent to the plane at points D and F (see Fig. 21.2) – these, it turns out, are the foci of the ellipse produced by the cutting plane.

Let T be a point on the ellipse produced by the cutting plane and let SNTM be the generating line of the cone that passes through T. Then since TM and TD are tangents from T to the sphere, MT = DT. Similarly, TN = TF. Therefore, DT + TF = MT + TN = MN, which is constant.

The Dandelin spheres illustrate well how a mathematical development grounded in a historical text can be enlightening and useful in a classroom presentation. But how far can one say that this grounding in history is the essential element in the mathematical presentation? What really is the role of the historical context? Having shown the basic idea of the Dandelin spheres, Boag says, "Before continuing with the mathematics, I will give a brief biography of Dandelin" (p. 35). Three short paragraphs follow providing a few biographical details, the name of Dandelin's paper on the Dandelin spheres and where it was published, and then some further work by Dandelin following the 1822 paper. What I want to stress is not that Boag should have given more historical information – for the paper, in many ways a very good one, was meant to be short from the start – rather, it is that the historical background and mathematical content are taken as separable. The mathematics is stopped and then continued after the history; it is not continued into the history, nor is the history continued into the mathematics. If the Dandelin spheres were presented to a reader of Boag's article without ever

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[18] Dandelin's diagram shows a planar section, with no perspective and no variation of line types, as I have done here; however, the lettering is consistent with Dandelin's. In her paper, Boag gives Dandelin's original diagram in facsimile as well as her own.

mentioning Germinal Pierre Dandelin, they would possess no less explanatory power and probably no less charm.[19]

In the examples of the curricular theme so far, the position assumed with relation to the past is very similar to that of "the treasure-hunter" described above: one dips into the past to pull out some beautiful example or approach, like the Dandelin spheres, which one can then use in the classroom. It is a completely legitimate way of using history, and it is legitimate to call it a historical approach, *if*, paradoxically, one accepts that there is a mathematical content that can be set off from all considerations of time, culture, and place: the gold one digs up may come in the form of unfamiliar coins, but it is gold nonetheless.

The genetic approach, which we have also included within the curricular theme, is much more subtle and places historical development at the center of its attention since it is there it finds its key to how students understand mathematical ideas and how they can learn to understand mathematical ideas better. As we said above, a teleological viewpoint is almost unavoidable in the genetic approach, and it is for this reason that the same mathematical ideas as those comprised in a modern curriculum can be assumed to exist, at least implicitly, in historical texts; this, in turn, proves the relevance of historical texts to the modern classroom. Again, the relation to the past implied by the genetic approach tends towards that of the "privileged observer."

To see how the genetic idea is expressed in current ideas about history of mathematics in mathematics education, however, we shall have to take a fairly general definition of it: we shall include in it any position that sees historical development as providing light on educational processes, students' learning and understanding, by somehow running parallel to these.[20] It will become apparent, though, that the genetic idea, viewed loosely as I intend to do, leads easily into the cultural theme, which undeniably tends away from a teleological viewpoint.

One year before Toeplitz's *The Calculus: A Genetic Approach* (Toeplitz 1963) appeared in English, the genetic approach appeared explicitly in a famous memorandum published in *The Mathematics Teacher* and *The American Mathematical Monthly* (Memorandum 1962). The memorandum was signed by 64 mathematicians but was, apparently, mainly the work of Lipman Bers, Morris Kline, George Pólya, and Max Schiffer, and, of those, mainly, Morris Kline (Roberts 2004). The paper was a thinly veiled attack on the curricular reforms forming the "new math" movement,

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[19] The point, I must emphasize, is not that the Dandelin spheres have no historical interest. They do! As one of the anonymous reviewers of this chapter emphasized, correctly, Dandelin's ideas are indicative of the atmosphere created by Gaspard Monge's teaching at the École Polytechnique, where Dandelin was a student. This may provide a hint as to why Dandelin's spheres had to wait until the 19th century to be born. My point here is that these matters played no crucial role in the article which I have discussed, nor, *given the general orientation of the article*, did they have to.

[20] In this way I am allowing the views of Sfard (1995), Dubinsky et al. (2005), and others inspired by Piaget's ideas in *Genetic Epistemology* (1971) to come within range of genetic approaches, even if Schubring (2011) claims, with some justice, that Sfard, for example, misunderstands Piaget in this connection and adopts only a primitive form of parallelism.

chief among them the *School Mathematics Study Group* (SMSG), headed by Edward Begle. The writers warned that it would "be a tragedy if the curriculum reform should be misdirected and the golden opportunity wasted" (p. 189), and, therefore, they would set out "fundamental principles and practical guidelines."

The paper then goes on to discuss seven guidelines of which the fifth is "genetic method." For Kline and the others, the genetic method furnished the ground for a direct attack on the thinking behind the "new math," namely, that when it comes to teaching and designing a curriculum history is a more dependable guide than the logic of an axiomatic system. Thus the memorandum states:

> This genetic principle may safeguard us from a common confusion: If A is logically prior to B in a certain system, B may still justifiable precede A in teaching, especially if B has preceded A in history. On the whole, we may expect greater success by following suggestions from the genetic principle than from the purely formal approach to mathematics. (pp. 190–191)

It is hardly surprising then that when Edward Begle responded to the memorandum (Begle 1962), he was conciliatory on most points *except* for the genetic principle. About that, he said it would "…require children to learn to compute with Egyptian, Babylonian, Greek and Roman numerals before being introduced to the historically later but far more efficient place value decimal system" (p. 426).

It is worth noting, too, that this exchange, in which the genetic approach was endorsed on the one side and rejected on the other, happened to be between one group of prominent mathematicians and another. For although it is not wrong to refer to the SMSG, and "new math" movement in general, as "mathematician-dominated" (see Amit and Fried 2008), it is important to realize that in a historical framework for education guided by the genetic principle, one finds a framework as congenial to the modern mathematician as the formal-axiomatic one. Kline, it should be kept in mind, was himself a research mathematician, and he well understood that, logically, the ideas of sequence, limit, and convergence precede derivative and integral; yet, when he wrote his own calculus textbook (Kline 1977), he had no qualms about beginning with the derivative.

For education, naturally, the attractiveness of the kind of parallelism represented by the genetic approach lies in its potential to provide clear concrete models for teaching and for understanding students' learning. This potential, so clearly assumed in the 1962 memorandum, is still adduced, albeit in a more qualified tone. Thus following Victor Katz's paper on the development of algebra in the special issue on history of mathematics in *Educational Studies in Mathematics* (volume 66, number 2),[21] Bill Barton writes in his "Commentary from a mathematics educator" that "To the extent that the ontogenetic argument is useful in mathematics education, this reflection should cause us to rethink some current trends" (Katz and Barton 2007, p. 198). In that same issue, Yannis Thomaidis and Constantinos Tzanakis take up the theme in a more focused way in their paper, "The Notion of Historical 'Parallelism'

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[21] I mention the special issue explicitly since it was one of the few instances that history of mathematics was given such broad attention in a leading research journal for mathematics education.

Revisited: Historical Evolution and Students' Conceptions of the Order Relation on the Number Line" (Thomaidis and Tzanakis 2007). Thomaidis and Tzanakis offer there what they see as empirical evidence both that students produce solutions to problems analogous to historical solutions and that they encounter difficulties which also follow a historical pattern.

That students' conceptual difficulties or epistemological obstacles[22] run parallel to conceptual difficulties in history has been taken up before (e.g., Katz et al. 2000; Bartolini Bussi and Sierpinska 2000; Herscovics 1989). Dorier (1998), for instance, uses history to identify students' problems with notions from linear algebra such as dependence. Among other things, he shows how Euler's notion of "inclusive dependence," as Dorier refers to it, the implicit redundancy of equations, is similar to students' conceptions and is what students need to overcome in order to arrive at more general notion of linear dependence: "Their concept of (in)dependence is, like Euler's, that of inclusive dependence and not linear dependence," he says (Dorier 1998, p. 150, see also Katz et al. 2000, p. 150). Plainly, this is a weaker application of the genetic principle than the traditional one in which students' learning of mathematical ideas actually recapitulates the historical development of those ideas; but it is also one much easier to swallow. That may be simply because these conceptual difficulties are truly difficulties, and one must contend with them whenever one faces them. On the other hand, is it not arguable that the compelling need to face these difficulties in the first place is a sign of their constant reoccurrence, strengthening the recapitulation theme? This is one possibility. But it is also possible that the reoccurrence of conceptual difficulties or any of a range of mathematical ideas is not because history and individual development proceed along parallel tracks, but because individual development is actually a *function* of historically conditioned ideas. In other words, the reoccurrence of mathematical ideas in individual development might be because those ideas and their mode of development are embedded in the culture in which children's mathematics education is situated.

21.3.3 The Cultural Theme

While one might strain to turn this latter possibility into a variant of the genetic position having a distinctive mechanism for individual development, it is more clearly a position directly opposed to a genetic position. Thus, Luis Radford and Luis Puig (Radford and Puig 2007) (see also Furinghetti and Radford 2008), who call this position, appropriately, the "embedment principle," write:

> Biological or natural developments unavoidably become *affected* by and *entangled* with the historical-cultural one as individuals use signs and other cultural artifacts, such as language. In fact, the merging of natural and historical developments constitutes the actual line of

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[22] This term stems from Bachelard's work on the history of science (Bachelard 1938) and then adapted for mathematics education prominently by Brouseau (see Brousseau 1997, pp. 98ff).

> growth of the individual. Given that it is impossible to untie the merging of the cultural and the natural lines of development, the conceptual growth of each individual cannot *reproduce* a historical-social conceptual formation process. In short, phylogenesis cannot recapitulate ontogenesis. (pp. 147–148)

Radford and Puig's embedment principle, which sees our thinking in mathematics as "…related in a crucial manner, to a historical conceptual dimension ineluctably embedded in our social practices and in the signs and artifacts that mediate them" (Radford and Puig 2007, p. 148) brings us squarely into what we called above the cultural theme. One sees immediately how the entrance into that theme is accompanied by the introduction of new subthemes, specifically, ones connected to semiotics, language, and social practices. Radford, for example, draws together these subthemes and their relationship to an historical approach in, among other places, his "On the epistemological limits of language: mathematical language and social practice during the renaissance" (Radford 2003). Even linguistic theorists such as Ferdinand de Saussure (1857–1913), one of the founders of modern semiotics, begin to have relevance in thinking about history of mathematics in mathematics education. Indeed, the idea of language as a semiotic system with both synchronic and diachronic aspect can be shown to be a good model for thinking about the seemingly fixed structure of mathematics and its simultaneous existence as a culturally engendered system changing over time (see Fried 2008, 2009).

Whether or not one takes the cultural theme as far as Radford and others have into the world of semiotics, the theme always carries a sense that mathematics and culture are inseparable, and this means that mathematics and history are inseparable. In a certain sense, this is no more than a very conscious recognition that mathematics is a human enterprise. Accordingly, in his paper, "The necessity of history in teaching mathematics" (Rickey 1996), Fred Rickey tells us that the point he wants to argue is that,

> …Mathematics is the work of individuals. It is a discipline that has been developed by many people over the ages, some making great contributions, some making minor contributions, with the cumulative effect that mathematics has developed into a rich field that has had a significant impact on the way people view their world.
>
> As teachers of mathematics, and even more so as historians of mathematics, we arethe carriers of the mathematical culture. It is our solemn responsibility to transmit this culture to our students. (p. 252)

This aim to humanize mathematics admittedly comes dangerously close to the trivial storytelling we have seen in Lightner's (2000) "Mathematicians are human too," but whereas "humanizing mathematics" there only meant making mathematics less formidable so students might not feel threatened by it and shun it as somehow inhuman, "humanizing mathematics," here, it means seeing mathematics as an *essentially* human activity, that is, as part of the *nature* of mathematics. It becomes a human science almost in the sense of Dilthey's *Geisteswissenschaft*, and, in this sense, the history of mathematics no longer functions only as a means used to promote motivation or interest but as something at the core of mathematics and, accordingly, of what it means to learn mathematics.

As an expression of culture, one's perspective on mathematics changes radically. For it brings to mathematics a conception foreign to the usual one in which mathematical objects and relations are eternal, ideal Platonic entities, everywhere viewed in the same way and everywhere given the same weight, ideas with no geography and no past. Such a change in perspective does not mean necessarily that relativism becomes the philosophy of mathematics, but it does invite a pluralistic view in which one does not assume that mathematics always and in all places means the same thing and is directed towards the same phenomena (needless to say, this is not a claim that everyone is always right and no one is ever wrong!).

With this in mind, one can see how the history of mathematics in mathematics education finds much in common with the still-developing subfield of mathematics education known asethnomathematics (e.g. D'Ambrosio 2006). Thus in their paper for the ICMI study volume on history in mathematics education (Fauvel and van Maanen 2000), Lucia Grugnetti and Leo Rogers (2000) emphasize mutual relations between history of mathematics and multicultural issues. In particular, in their view, the history of mathematics helps the student acquire a sense of diversity, of the many different ways people can think about and approach the world:

> Multiculturalism then, in the sense that we have tried to convey here, is the identification and celebration of diversity, the respecting and valuing of the work of others, the recognition of different contexts, needs and purposes, and the realisation that each society makes and has made important contributions to the body of knowledge that we call mathematics. (p. 51)

The idea of diversity is not only a central idea in all cultural studies, it is also a central notion in all historical studies, mathematical or not. In this way, the cultural theme comes closest to a historical approach to mathematics education that is truly historical. Yet, as we shall see shortly, this brings us into a difficulty when we consider history of mathematics in the context of other legitimate goals in mathematics education. To see this we shall have to get a better sense for what it means to be historical – and *non*-historical.

21.4 History of Mathematics as History and What That Implies for History of Mathematics in Mathematics Education

Although there is no complete agreement on what history is and what is at the heart of the historian's craft, still, there are undeniable commonalities.[23] Of these, a keen awareness of the tension between past and present or, at very least, the need to confront the question of past and present, stands out most clearly. For while it is impossible to think of history without reference to the past, history is not solely about the past; it is also about the present. To start, one must refer to the present to the extent

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[23] Much of this section is based on a plenary talk (Fried 2010) at the ESU-6, HPM conference in Vienna, July, 2010.

historians' materials, their objects of study, are things having made their way into the present. With this in mind, Geoffrey Elton (1967) defined history as being "… concerned with all those human sayings, thoughts, deeds and sufferings which occurred in the past and have left present deposit; and it deals with them from the point of view of happening, change, and the particular" (p. 23).

The qualification in Elton's statement emphasizes also that it is not just past or present that is essential but how these are treated, namely, "from the point of view of happening, change, and the particular." The historical mode of thinking demands treating these "survivals" from the past, as Michael Oakeshott calls them (see Oakeshott 1999), precisely *as* survivals, survivals from another world. One interrogates them to understand where they came from – for theirs is a world not conditioned by the existence of ours, yet it is one out of which ours has grown.

History, viewed in this way, is a kind of vicarious experience of the past through what has made its way into the present. Oakeshott, whom I have just mentioned, views history for this reason as a mode of experience, and, for him, to experience the past in the present *as history,* one must view the past *unconditionally*. The historical past is a kind of past, but there are other kinds of past as well. To describe a relationship to the past that depends on the present, in other words, that sees the past in terms of present values, needs, and ideas, Oakeshott uses the term "practical past." The historical past is defined in opposition to the practical past; it is a past understood in terms of its separateness from the present.

Accordingly, in his chapter on historical experience in *Experience and Its Modes* (Oakeshott 1933), Oakeshott sets out the historian's task as follows:

> What the historian is interested in is a dead past; a past unlike the present. The *differentia* [emphasis in the original] of the historical past lies in its very disparity from what is contemporary. The historian does not set out to discover a past where the same beliefs, the same actions, the same intentions obtain as those which occupy his own world. His business is to elucidate a past independent of the present, and he is never (as an historian) tempted to subsume past events under general rules. He is concerned with a particular past. It is true, of course, that the historian postulates a general similarity between the historical past and the present, because he assumes the possibility of understanding what belongs to the historical past. But his particular business lies, not with this bare and general similarity, but with the detailed dissimilarity of past and present. He is concerned with the past as past, and with each moment of the past in so far as it is unlike any other moment. (p. 106)

So even though historical experience is an experience in the present and one belonging to a living and breathing historian, the historian must live by the desideratum to view the past in its particularity. Historians' rule to avoid anachronism is an easy corollary to this desideratum. However, it is not an easy rule to obey, since we are beings who live in the present and whose immediate experience is not that of the historical subjects we study. The struggle with anachronism is at the heart of the tension between past and present, with which I began this section. It might be said, indeed, that the historical art is one that aims to keep that struggle alive.

The dangers of submitting to anachronism and the subtle ways in which it can subvert history were discussed most trenchantly and colorfully by Herbert Butterfield in his classic, *The Whig Interpretation of History* (Butterfield 1931/1951). The term "Whiggism" has subsequently entered the vocabulary of standard historiography.

The tendency it refers to is the distorting of the past not only by reading modern intentions and conceptions into the doings and writings of thinkers in the past, which is anachronism in its most direct form, but also by forcing the past through a sieve that bars ideas foreign to a modern way of looking at things and permits those adaptable to modern interests. For example, in reading Proclus' *Commentary on Book I of Euclid's Elements*, a Whig historian would leave out Proclus' arguments in the "first prologue" about the nature of mathematical being and role of mathematics in the moral education of the soul while emphasizing Proclus' comments on logical difficulties, missing cases, and alternative proofs connected with the familiar geometrical propositions in the *Elements*. These things are truly to be found in Proclus, but a Whig historian would give the impression that they are the *only* things in Proclus, or the only things of any worth in Proclus.

Whig history is indeed particularly seductive when it comes to mathematics. This is because, as we have remarked before, mathematics is easily taken to be a constant component of thought not only in the modern world, but also in all parts of the world and at all other times. Left unchallenged, that view of mathematics makes Whiggism almost inescapable: present mathematical knowledge, short of logical errors, is mathematical knowledge *tout court*; past mathematical knowledge, to be understood, has merely to be translated into a modern idiom. So one can feel fully justified in treating mathematicians of the past as Littlewood famously said of the Greek mathematicians, that they are only, "Fellows of another college" (quoted in Hardy 1992, p. 81); mathematicians of the past, like one's colleagues, are useful for gaining insights into one's present mathematical research. The past, for Whig historians, is thus almost *by definition* a "practical past," adopting Oakeshott's term: they seek in the past what is useful for the present.

Clifford Truesdell (1919–2000) is a good example of a Whig historian. He is a good example, not because his historical work was false or inaccurate or superficial, but precisely because he was tremendously learned and serious; his work was thorough and in some ways deep. The problem is only how his history was oriented, and how much *historical* understanding we gain from it. For him, history of mathematics was unabashedly dedicated to a "practical past": "One of the main functions [the history of mathematical science] should fulfill is to help scientists understand some aspects of specific areas of mathematics about which they still don't fully know" (in Giusti 2003, p. 21). What one learns from the history of mathematics, in its Whiggish form, is, in short, mathematics.

By now it should be apparent that this view of mathematical past as a "practical past" lies close to the foundations of the curricular theme. The very fact that history, in the curricular spirit, is seen as something *to use* in order to promote modern mathematical knowledge brings it into line with the practical past and the Whig interpretation of history. It must be made clear that the problem is not that proposals according to the curricular theme have no good effect for learning mathematics; it is its historical character that is in question. For to the extent that mathematics is continuous over time and place, a universal body of content, it is really ahistorical and noncultural, or, at best, its peculiarly historical and cultural aspects involve only trivial matters of form. Besides this kind of history being thus non-history, by using the present to determine what is useful for the present, one finally forfeits *learning* from the past. It is this that Butterfield found so wrong about Whig history. More specifically, he writes:

> If we turn our present into an absolute to which all other generations are merely relative, we are in any case losing the truer vision of ourselves which history is able to give; we fail to realise those things in which we too are merely relative, and we lose a chance of discovering where, in the stream of the centuries, we ourselves, and our ideas and prejudices, stand. In other words we fail to see how we ourselves are, in our turn, not quite autonomous or unconditioned, but a part of the great historical process; not pioneers merely, but also passengers in the movement of things" (p. 63)

By contrast, history of mathematics in mathematics education according to the cultural theme with its interest in difference and the essential human imprint in mathematical thought is consistent with a truly historical mode of thinking and assumes that one can learn something from history as such. Indeed, it assumes one can learn about ourselves as beings for whom mathematics is part and parcel of our cultural identity,[24] and, as Butterfield warned, we shall fail in this if we too easily adopt a history guided by the present. Put in different terms, ones inspired by Anna Sfard's work on "meta-discursive rules" and "commognition"[25] (Sfard 2008), Kjeldsen and Blomhøj (2011) have stated the case thus:

> As active learners, students can become aware of their own meta-discursive rules by identifying the meta-rules that governed the mathematics of the past and comparing them with meta-discursive rules governing the mathematics of their textbook and instruction. In this way, opportunities for students to experience commognitive conflicts are provide and proper changes can be initiated. (pp. 4–5)

But even in these different terms, Kjeldsen and Blomhøj are fully aware that what stands opposed to these opportunities is Butterfield's Whig history, as they immediately point out (p. 5):

> If one's reading and interpretation of historical sources are constrained by the way mathematics is perceived and conceptualized in the present, the historical text cannot play the role of an "interlocutor" that can be used to create commognitive conflicts, as explained above, when students communicate with the text, since differences in the way of communicating in the past and in the present will have been "washed away" by the whig interpretation. (p. 5)

The conclusion seems to be clear. In order to have a historical approach in mathematics education in which history is taken seriously *as a form of knowledge*, we ought to embrace an approach along the lines of the cultural theme and reject the Whiggish proposals derived from the curricular theme. But there is a difficulty here. For one cannot forget that mathematics educators are not historians and have other legitimate concerns. So while the history of mathematics can bracket the present in order to understand the past, mathematics education typically justifies itself precisely by the power and

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[24] One recalls in this connection Collingwood's claim that this kind of self-knowledge is the entire point of history (e.g., Collingwood 1939).

[25] In creating this term – a fusion of the words "communication" and "cognition" – Sfard tried, in a Vygotskian spirit, to capture the way thinking is entangled with discourse.

necessity of mathematics in *modern* contexts, in science, engineering, economics, and industry. This is certainly consistent with the spirit of the American *Principles and Standards for School Mathematics* (NCTM 2000). There, we read:

> The level of mathematical thinking and problem solving needed in the workplace has increased dramatically.
>
> In such a world, those who understand and can do mathematics will have opportunities that others do not. Mathematical competence opens doors to productive futures. A lack of mathematical competence closes those doors.
>
> …More students pursue educational paths that prepare them for lifelong work as mathematicians, statisticians, engineers, and scientists.
>
> …Today, many students are not learning the mathematics they need. In some instances, students do not have the opportunity to learn significant mathematics. In others, students lack commitment or are not engaged by existing curricula. (NCTM 2000, Introduction)

One cannot belittle this emphasis on modern mathematics: the ideas and methods of modern mathematics are undeniably profound and powerful, and there is no reason they should not be pursued and taught. But accepting this kind of emphasis also means that mathematics educators *cannot* bracket the present, as historians can and must. Thus, when mathematics educators – even those with real historical sensitivity and knowledge – confront a chapter in the history of mathematics they must heed, to some extent at least, the counterweight of their obligation to teach mathematics in a modern spirit. They must consider how relevant the chapter is to the modern mathematical ideas they need to convey, how well it fits the subjects required by their curriculum. Seemingly practical considerations of time and scheduling are, in fact, signs that history of mathematics in the classroom must be subordinated to such standards as those in the NCTM document.[26]

Naturally, there may be some historical topics for which a happy medium can be found, some cases where a chapter in the history of mathematics fits comfortably in the curriculum without demanding too great a compromise as to its historical character. While this may be, it is not the point. The point is that when mathematics education emphasizes mathematics as it is understood and practiced today, as it is needed in science and engineering, it will be necessarily predisposed to treat the history of mathematics in a Whiggish spirit, separating relevant from irrelevant ideas according to the needs of the modern curriculum. This predisposition is not an injunction to be Whiggish; it is, rather, a kind of ineluctable internal pressure at work in any attempt to introduce history of mathematics into mathematics education, where the latter is directed, as it generally is,[27] towards modern mathematics.

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[26] One might also cite European standards as well, even the Danish competence-oriented mathematics education, KOM-project (see Niss and Højgaard 2011). The latter, however, includes competencies that invite a broader view of what it means to be mathematically educated (see Jankvist and Kjeldsen's (2011) paper and also the discussion below).

[27] There are, of course, exceptions. One of the anonymous reviewers of this chapter made me aware of the Ross School and Institute in New York State, USA, whose program, among other things, stresses cultural history. Describing their "spiral curriculum," they write: "Teaching the humanities and sciences in the context in which they historically emerged makes for a naturally integrated approach" (http://rossinstitute.org/#/The-Ross-Model/Spiral-Curriculum, accessed April, 2012).

Mathematics educators, in this way, are placed in a very different position from the historian of mathematics who must struggle with the problem of anachronism. For the historian, engaging in that struggle is part of what it means to do the history of mathematics: historians who do not live in the tension between past and present are not true historians. But in the case of mathematics education, the problem is one of conflicting demands and commitments, presenting the mathematics educator with a dilemma: maintain modern mathematics as one's main end and thus subordinate history of mathematics serve modern ideas and needs, that is, adopt a Whig version of history of mathematics, or insist that history of mathematics be history and put aside the perfectly legitimate emphases of programs seeking to help students use and understand the modern mathematics essential for all the pure and applied sciences (see Fried 2001, 2007 for further discussion and additional examples).

Of course the force of the dilemma derives from accepting prescribed ends like those described in the example of the NCTM. And one must emphasize that built as they are on the power of modern mathematics to address societal and scientific needs, those ends are anything but inconsequential and easily dismissed; however, they are not absolute. What it means to teach mathematics and what it means to be mathematically educated can be defined in accord with a different set of ends, ones more cultural and humanistic and less utilitarian. Mathematics education may not be so determined that it must follow the standards set out in the NCTM Principles and Standards (NCTM 2000) or similar documents (e.g., European Mathematical Society 2001). Mathematics education can be reconceived so that it promotes an educational approach shaped by history of mathematics as a form of knowledge rather than one that only uses history of mathematics in the service of ends not necessarily in line with those of history, "history as a goal" rather than "history as a tool," as Uffe Jankvist has aptly put it (Jankvist 2009).

Reconceiving mathematics education in this way does not mean turning it into what has derogatorily (and somewhat unfairly) been called "mathematics for poets"[28]: it can be rigorous and, yes, mathematical. Although there is no single scheme for this, it is clear that, one way or another, the presence of original sources will be essential. This is because, as Elton (1967) made plain in the passage quoted above, at the heart of the historical enterprise are those thoughts – in our case mathematical thoughts – "…which occurred in the past and have left present deposit…" (p. 23) In the case of the history of mathematics, as with all history of ideas, the present deposit consists, maybe not exclusively, but certainly chiefly of written texts. For while written texts in general history are crucial *as accounts* of happenings in the past, in the history of thought, texts are, one might say, the thought itself. Original mathematical texts are also the chief expression of how mathematicians have sought to engage other mathematicians in their thought; they represent communicated thought. And that, bringing us back to the cultural theme, places original texts at the center of what we should call mathematical culture and tradition.

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[28] Poets can have a deep knowledge of mathematics. The mathematical knowledge of the great French poet, Paul Valéry, for example, could hardly be called superficial or soft.

Tradition is too often misunderstood as something rusty and dogmatic. With Eva Brann, “By *the tradition* I mean neither the old customs nor the recent routines, neither the sedimentary wisdom nor the petrified habits of communities. I mean, to begin with, *a collection of books*” (Brann 1979, p.64). And as Brann also points out, the origin of the word “tradition,” the Latin verb “tradere” means both to pass on and to betray (p. 67). In other words, tradition implies not only what one remembers and respects but also the platform from which one changes and develops. It is in this sense, then, that one should understand tradition when it comes into the arguments of those who promote the use of original sources in teaching mathematics. For example, Laubenbacher, Pengelley, and Siddoway (1994)[29] write this in defense of using original texts:

> For a novelist, poet, painter or philosopher such observations would be old news, since their disciplines have long recognized the importance of studying the original work, techniques and perspectives of classical masters. And in so doing, they are never removed from an understanding of how people have struggled, and have created works of art. Young artists thus see themselves as part of a creative tradition. Unfortunately, we have lost this sense of tradition in our discipline, and, ironically, we can perhaps blame much of this loss on the dazzling explosion of mathematics in this century. It is time we step back from our accomplishments and recapture a historical perspective.

The picture of mathematics education, or rather of becoming educated mathematically, that begins to emerge is not so much one that concentrates on the mastery of certain techniques in mathematics or even certain concepts in mathematics such as a function or derivative, but on the reading and learning to read a body of mathematical texts. Which texts to be included and which not, aside from certain texts, such as Euclid’s *Elements*, could no doubt be debated; even courses on Shakespeare vary as to which play or sonnet is discussed, alluded to, or left unmentioned. And mentioning literature is not by accident: reading of texts, following authors’ modes of presentation and their points of attention, weighing the cultural context of works, and so on would make mathematics education into a kind of literary education. And yet it *is* mathematics, as one quickly finds out working through Euclid’s *Elements*, Descartes’ *Géométrie*, or Euler’s *Introductio*.

But using original texts is only a condition for a mathematics education for which history is a goal; one must know how to use original texts. While this involves theoretical considerations concerning the role of original source material, it also involves considerations arising from empirical studies. As Furinghetti et al. (2006) point out, “An important development in recent years is that more empirical research studies on the integration of original sources are being done, many of which include a large number of students” (p. 1288).

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[29] Laubenbacher and Pengelley have promoted the use of original sources indefatigably for over twenty years with such works as (Laubenbacher and Pengelley 1999). In the latter, for example, they treat analysis by looking closely at the transitions of ideas connected with the calculation of areas and volumes, and do so via texts from Archimedes,Cavalieri, Leibniz, Cauchy, and Abraham Robinson. An overview of their work can be found at the website: http://math.nmsu.edu/~history/

One good example of this sort of empirical study is that by Jankvist and Kjeldsen (2011) (also described in Kjeldsen and Blomhøj (2011)). This research was carried out against the background of Danish competence-oriented KOM-project report, which emphasized history of mathematics in what it termed “overview and judgment,” competences referring to “mathematics as a discipline” (Niss and Højgaard 2011, pp. 118–120).[30] In the course of the study, high school students worked on problem-based mathematical projects over the course of a semester with close attention to history via original sources (in translation) such as Johann Bernoulli’s 1691 “solution of the cable problem” as well as more modern works, such as Hamming’s 1950 “Error Detecting and Error Correcting Codes,” treated in a historical spirit. By assuming a problem-based approach, Jankvist and Kjeldsen tried to achieve a situation in which close attention to written texts and sensitivity to history as history, attention “meta-issues,” was “anchored” in the “in-issues” of mathematics, as they put it. Although there was a risk of making the in-issues *the* issues, and, therefore, descending into Whiggism, they could avoid that and keep “history as a goal” partly through this close attention to texts and partly through the constant interaction with historically knowledgeable supervisors.

The genetic principle is an obvious and in some ways natural basis for using original texts. Because the principle assumes that history follows a course towards a given modern topic that mirrors the course of students’ own of understanding, it is reasonable, on that basis, to present texts one after another in historical sequence. Michael Glaubitz (2010) obtained empirical data on this point by comparing the genetic approach and a conventional nonhistorical approach. His experiment centered on 175 students using the quadratic equation and formula as his topic and works by Al Khwarizmi, for example, as his texts. Even with respect to interest, Glaubitz’s results were disappointing. He summarizes them as follows: “…this teaching did not work. The students rather got confused and appeared very displeased in the end” (p. 8). Naturally, one should be cautious here: the texts were given to the students and then followed by “conventional exercises, problems and applications with modern methods” (p. 5); there may be other ways to pursue a purely genetic approach.

But Glaubitz also examined another approach, that developed by Niels Jahnke, the “hermeneutic approach.” Students in this approach were taught the quadratic equation and formula in a modern conventional way, and, when they were brought face to face with the original texts, they were asked to engage with them in active, often creative, ways, such as writing fictitious interviews with Al Khwarizmi: the original texts were still present, but the students’ own perspective in reading them (including some of their difficulties in reading them) were taken into account. The results here were much more encouraging and contrasted starkly with the approach based on the genetic principle.

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[30] It is this looking at mathematics as a discipline, from the side as it were, that gives the term “meta-issue,” used by Jankvist and Kjeldsen its aptness. Jankvist and Kjeldsen’s complementary term, I might add, is “in-issue,” by which they mean an internal matter of mathematical content – concepts, methods, algorithms, mathematical proof, etc.

By having students learn, say, the quadratic formula, in a modern way, one might think that the hermeneutic approach is actually introducing anachronism into its historical approach. But, as we discussed at the very start of this part, while a historical understanding of the past demands seeing the past unconditionally, it does not require one to forget the present. We were at pains to show that a historical understanding is marked by a tension between past and present.[31] The problem with, for example, Whiggism is that it sees the present as completely consistent with the past – hence, no tension. When one sees, from the start, that one's position with respect to the past is problematic, one is thrown into the role of being an interpreter. As Jahnke (2000) puts it[32]:

> In traditional theories of hermeneutics the relation between the historical meaning of a text(the intention of its author) and its meaning for a modern reader is amply reflected and identified as the essential problem of interpretation. In fact, seen under the aspect of method, history of mathematics, like any history, is essentially an hermeneutic effort. If history of mathematics is not to deteriorate into a dead dogma, teachers should have some ideas about the hermeneutic process and the fruitful tension between the meaning of a text in the eyes of its author and the meaning for a modern reader. (p. 298)

To use the terminology mentioned in part 2 of this paper, in the hermeneutic approach, one's position with respect to the past is distinguished by being in the present and having present mathematical knowledge, but it is not "privileged." On the contrary, recognizing our position in the present *as present* comes with the recognition that the past is obscure, and, thus, needs to be interpreted. And the phenomenon that is familiar to anyone who has done serious historical work is that more one engages in that interpretive activity the more obscure the past becomes. But this only brings the distinctness of one's modern knowledge into relief. One truly begins to see here how one can bring a historical awareness into mathematics education that will allow not only for genuine insight into the past but also into the present.

21.5 Conclusion

With the discussion of tradition and of interpretation, we come full circle in this chapter and, in certain respect, historically as well. For recall, the word "tradition" was also one translation of the Greek word *paideia*. Its other translations, as we noted earlier, included "education," "civilization," "culture," and, in Latin, *humanitas*. These are all themes that have been central in this chapter. But more than that the tacit message here has been that by taking history of mathematics as a goal, we might be able to restore a sense of mathematical knowledge as the self-knowledge

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[31] This awareness of the tension between the students' own perspective and that of the original texts also played a part in Radford and Guérette's (2000) successful teaching sequence concerning the quadratic equation and the Babylonian's "naive geometry."

[32] Another account of the details and presuppositions of the approach can be found in Jahnke (1994).

of our human mathematical mind, to paraphrase Collingwood (see Fried 2007): the mathematical mind is indeed a human mind, and doing mathematics is a high human activity. *Paideia* carried that sense of a distinct human possession relating to humanness in its highest and broadest expression.

Now we first mentioned *paideia* in connection to the history of mathematics in ancient education and, specifically, to Proclus. Tradition as historical character in that context had to be taken in a qualified way: mathematical tradition for Proclus was much more of a continuous tradition than it is for us. Thus Proclus' references to mathematicians of the past could genuinely be seen as they were references to "colleagues" no longer alive. For us, there have been breaks in the tradition even though it is still in some sense ours: the past for us is a past that has often been lost or obscured and that requires recovery and interpretation. Our own sense of who we are with respect to our mathematical past requires cognizance of these breaks and the fundamental differences between us and our predecessors. History in the modern sense of Elton, Butterfield, and Oakeshott, while it recognizes commonality, endeavors to refine our understanding of such differences. For this reason, in the development above, it was crucial to confront the historical character of attempts to incorporate history of mathematics in mathematics education, to point out the teleological assumptions of the genetic principle and the inadequacies of the motivational and curricular themes, for example.

The answers to such criticisms, I have suggested, require more than patches. They require perhaps a reorientation vis-à-vis the question of history of mathematics in mathematics education. Instead of asking how we can produce a presentation or program here, a chapter or unit there in the history of mathematics fitting the needs of a set curriculum or addressing the lack of motivation of our students, we may need to ask how we can adjust the meaning of mathematics education itself so that it will accommodate history of mathematics pursued honestly and deeply. No attempt was made to floor an exact proposal because that cannot be done. However, an essential component of any such proposal, we argued, is a view of mathematics as a collection of texts that need to be studied, a collection of authors that need to be engaged. This too, we made clear, cannot be taken a simple proposal. There is more than one way to introduce original texts. A promising suggestion, both theoretically and practically, is Jahnke's hermeneutic approach, which involves both a modern, but not Whiggishly oriented, mathematical knowledge and also an awareness of oneself as an interpreter. The possibility of an approach like the hermeneutic approach makes the possibility of a mathematics education that is truly historically sensitive within reach. Perhaps, we will discover the way to a new *paideia*.

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Chapter 22
Philosophy and the Secondary School Mathematics Classroom

Stuart Rowlands

22.1 Introduction

Can philosophy have a role in the teaching and learning of mathematics in school? If it can have a role, what is it? There may be several answers according to several perceived roles, such as it enables pupils to think in the abstract, it contextualises an otherwise very formal subject, it situates mathematics in the realm of philosophy; but perhaps the most central answer to which most others are subordinate is that it can aid the understanding of mathematics. A class reflecting philosophically on the concepts of mathematics will most likely attain a deeper understanding of those concepts.

For example, a class reflecting on the difference in abstraction between one sheep and one sheep equals two sheep with $1 + 1 = 2$ (the latter concerns the concept of number; the former is a statement of physics similar to 'one lump of plasticine add one lump of plasticine equals one lump of plasticine'), reflecting on the nature of a geometrical straight-line (e.g. What is it? Can we see one? Does it exist? 'Could industrial artefacts such as aeroplanes and the associated machinery for production ever exist without it?' 'When did it first appear?') or discussing limiting cases to infinity, etc. will most likely develop a *relational understanding* (in the sense of Skemp (1976)) of how these concepts are embedded, connected and embellished in the relevant mathematics, as well as just knowing how to manipulate them according to the rules (Skemp's (1976) *instrumental understanding*). A qualitative understanding of infinity as a limit, with such examples as the proof for the area of a circle, deepens our understanding of why this area is πr^2, despite the unlikelihood of the class arriving

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at a formal definition of Cantor's infinities. An 'informal' treatment of infinity provides a means to understand why the area of a circle is as it is. This chapter discusses the ways in which philosophy can aid the teaching and learning of the content of secondary school mathematics and how it can also situate mathematics culturally and historically.

One possible objection is that it takes longer to develop a relational understanding than it does an instrumental one (e.g. it takes longer to show *why* the area of a circle is πr^2 than simply giving the formula), but it is shorter in the long run compared with committing to memory all the various ways to tackle a variety of questions with formulae and rule-of-thumb procedures that are given without reason. As Skemp (1971) states, many students pass a public examination in mathematics at one level, but inevitably fail the next level because there is no basis to understand the abstraction necessary for the next level. The student must first master the previous level, not only in terms of passing examinations but also in terms of a conceptual understanding of the relevant domain of knowledge – despite any public recognition of passing that level.

Although it will be argued that philosophical questions do presuppose answers that are right, the classroom discourse need not arrive at completeness for the value of the discourse to take effect. What is being suggested is that philosophy can enrich the subject, not only in terms of the subject coming alive but also in terms of understanding the subject, even if the class does not arrive at any formal definition normally expected at degree level. Another objection is that if the formalism is too difficult then the problem should not be introduced at the secondary school level. For example, if the vast majority of schoolchildren will fail to understand the theory of real numbers with proof, such as the density of the rational numbers and the existence of the irrationals, then the theory should not be introduced at this level. Hopefully, however, all secondary school pupils will have been introduced to the real numbers including the rational and irrational numbers; so why can't the theory of the reals begin here, even though the required formalism may not be reached at this level?

This chapter proposes philosophical discourse in the teaching of school mathematics,[1] with the teacher as a 'sage on the stage' orchestrating the class towards a target concept or a series of target concepts. Unfortunately this chapter seems alone in what it proposes. The literature mainly consists of the Philosophy for Children (P4C) programmes which advocate the teacher as a 'guide on the side' who allows the discourse to go much its own way without intervention. There is very little, however, on philosophy and the mathematics classroom, and the little there is has tended to be an extension of the P4C programmes, with the emphasis on whole-class discussion which Kennedy (2007) termed the 'constructivist classroom' with its egalitarian emphasis on shared meanings.

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[1] Unfortunately this chapter does not discuss philosophy and undergraduate mathematics as this deserves a chapter in its own right. At this level there is not only a change in content (with an emphasis on formalism and rigour) but also a variety of teaching/learning methods that may not be so appropriate at the secondary school level. Nevertheless Pincock's (2012) *Mathematics and Scientific Representation* would be most appropriate as a text for this level.

P4C advocates a circle or horseshoe of children discussing philosophy with the teacher acting as chair who helps steer the conversation without preconceived ideas as to what the children ought to learn from such a discourse – there is no imposition with what the teacher considers to be right or wrong. By contrast what this chapter proposes is indoctrination, but only in the sense that teaching mathematics is in itself a form of indoctrination: a social-cultural activity that inducts students into the best that has developed out of what is essentially a two and a half thousand year history.[2] It is not indoctrination in the sense of accepting something without reason.

This chapter begins with a literature review, and given the small number of articles on philosophy in relation to the secondary or primary school mathematics classroom, the review will focus on the P4C programme in general but with mathematics in mind, especially since the majority of the small number of articles on philosophy and the mathematics classroom are influenced by this literature.

P4C is not just a strand within education research but has now become part of the practice of teaching and has truly entered the public domain, in the UK at least. For this reason alone, the literature review is relevant given the present-day popularity of the programme, especially in England and Wales where the constraints of the National Curriculum and the excessive bureaucracy of accountability have made this programme very attractive to teachers, educators, curriculum developers and indeed the children themselves; but there is also a more overarching reason for the review – *it has made possible the arguments and proposals of this chapter*. Although this chapter's historical-cultural emphasis in the teaching of mathematics has already been formulated in previous articles,[3] this chapter's consideration of the role of philosophy in mathematics education has been influenced by its own review of the P4C programme. Although critical, this chapter owes a debt of gratitude to the programme in the sense that if the programme never existed, then many of the ideas of this chapter would not have existed either, certainly as far as the ideas of the author are concerned.

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[2] Although there were great mathematical advances prior to the Greeks, the Greeks created deductive proof and the necessary theoretical objects to accomplish it, culminating in the axiomatic framework of the *Elements*. There was nothing like it beforehand and nothing like it until the nineteenth century when much of mathematics was rewritten in axiomatic form. Prior human achievements in mathematics notwithstanding, Greek deductive geometry was the most stunning advance, and there is a sense in which 'history' begins two and a half thousand years ago – especially since over that period to learn mathematics was to learn the *Elements* (to the delight or chagrin of many pupils).

This is not by any means to undervalue the educational potential in introducing the mathematics of, for example, the Babylonians (is the 360° in the angle measure of a circle now a matter of convention or was there an objective reason for adopting it? Is there a need for base-ten compared with base-60? What prompted their recipe for what is today expressed as the quadratic formula?). However, this article is primarily about engaging pupils consciously with justification and proof, the abstract theoretical objects that were created for the purpose and the impact both culturally and cognitively.

[3] For a theoretical overview of this perspective see Carson and Rowlands (2007); for validation see Rowlands (2010).

Initially the review focuses on the controversies surrounding the programme in the UK, but there are no apologies for this. What is happening to education in the UK at the moment (which essentially began with state control) could happen elsewhere, but perhaps the most important aspect of these controversies is that we have the distinct advantage of observing a development in education research, one that is relevant to this chapter, put into practice with all the controversies from the public surrounding it. The fact that this is happening in the UK is in a sense irrelevant (although some of the issues surrounding its implementation are particular to the UK), and some light on the controversy not only shows what's at stake but also provides the context (or 'backdrop') for what this chapter proposes.

Section 22.2 discusses the present-day impact of P4C and the controversies surrounding its programme in the public domain. It also critiques a fundamental premise of the programme that children as young as five are natural philosophers, although this section does not deny that children do ask questions that can be considered philosophical. This section argues that children are not natural philosophers but they can be trained to think and discuss philosophically.

Although there is much written on the programme in the literature, there is very little on philosophy in the mathematics classroom. What little there is tends to frame philosophy and mathematics in the context of the programme, and this small sample will be critiqued in Sect. 22.3. Section 22.4 may be considered the heart of this chapter, because it puts forward the proposal that philosophy and mathematics can be introduced in a traditional classroom setting with the teacher taking the dominant role. It will be argued that under such a regime the teacher is not imposing her ideas on the class but is able to steer the class into thinking about what is being proposed in terms of philosophy and mathematics – the aim being a deeper understanding of mathematical concepts. Unlike most of the mathematics taught in many (perhaps most) UK classrooms, there will be very little room for faith. In such a programme, children will not be expected to accept the angle property of the triangle (that the three angles of a plane triangle add up to two right angles) because the teacher says so (or because a few triangles have been measured); instead, the class will be directed to consider the nature of deductive proof and to adopt a critical stance that demands justification. The class should then find it easier to construct the proof with just a few hints.

Perhaps the essence of this chapter is that philosophical discussion need never be far away from the many mathematical concepts that we teach. For example, the teacher could raise the question as to how it is possible for the area under a curve to be expressed as an exact number of square units. Exercises for 11-year-olds (or thereabouts) involving the approximation of area using finer and finer grids can provide the springboard for discussing limiting cases and hence the concept of a limit (qualitatively at least; any formalism should perhaps be left to a much later level of development).

The proposed philosophy may be loosely described as the philosophy of mathematics. Issues concerning Platonism and proof may certainly come under that category, but there are also other related issues which although applicable to the philosophy of mathematics are more to do with philosophy in general, such as

Plato's distinction between belief and knowledge. This chapter is more a proposal for philosophy in the broader sense than the specific philosophy of mathematics, but then elementary philosophy of mathematics cannot be separated from broader philosophical considerations.

Especially in a classroom environment, philosophical considerations of mathematical concepts can be a valuable aid in understanding those concepts. The first half of Sect. 22.4 is therefore given over to the added value of philosophy in the mathematics classroom prior to the main proposal presented in the second half, which is that this philosophy would be better framed within a historical-cultural context.

22.2 A Critique of the Philosophy for Children Programme

From small beginnings over three decades ago, P4C is now in the public domain. In the UK, hundreds of primary schools have timetabled philosophy discussions, and some private schools have their own resident philosopher. There are glossy journal front covers emblazoned with P4C and an ideological battle as to whether P4C is suitable for children, fought in the pages of the press with educational commentators and religious leaders on the offensive.

The front cover of the first edition of the Primary Teacher Update, a glossy journal presented upfront next to the candy at the tills of a particular W. H. Smiths, a very large retail corporation that mainly sells magazines and books, stated 'Philosophy for children. Encourage them to think' and shows two young children and their teacher engaged in conversation. The article is written by Lenton and Videon (2011), the founders of P4C, and iterates the misconceptions surrounding the implementation of philosophy for children. On what seems to be based on the P4C literature since the early 1980s, the article mainly provides (very brief but succinct) answers to the following: 'philosophy is too hard for children', 'you have to be academic to understand complex ideas', 'philosophy cannot be fitted into the curriculum', 'you have to be a specialist to teach it', and 'it doesn't have a purpose – what is the point?' Bearing in mind that this is for public consumption, the answers given by the article are too obvious and 'commonsensical'. For example, on the point that philosophy may be too hard for children, the article simply responds that children are naturally inquisitive and want to question. However, the inclination for young children to ask 'why?' may not be sufficient to overcome the difficulties of philosophical discourse. Taken in context, the article was not written for rigorous scholarly discussion, although the P4C academic literature *is* and for that reason is open to critique.

The Primary Teachers Update article is a push for P4C with an editorial giving this push a sense of urgency: we need to equip children with the tools to think independently if we are to avoid the mindless mob violence that has recently occurred across UK cities. P4C is more than trying to improve education in terms of children understanding what is taught across the curriculum (it is stressed that a little philosophical discourse in general can help to question and hence understand the concepts taught across the curriculum); it is also about improving society. P4C seems to have a far-reaching social agenda which some may find unjustified (e.g. can fundamental changes be made through philosophy?). The point is that P4C is now under public scrutiny and the stakes are high.

The article ‘Time to take the won’t out of Kant’ (Lightfoot 2011), emblazoned on the front cover of a magazine (*Tespro*) that comes with the *Times* Educational Supplement (a highly subscribed professional newspaper), outlines the P4C’s current influence and popularity and, with reference to a sympathetic psychologist who actually worked with Piaget, stated that Piaget seriously underestimated the capabilities of the young. It provides much information on relevant materials, where certain P4C programmes can be downloaded and in-service training venues, with the price tag. From relative obscurity P4C is now in the limelight, at least in the UK. It is seen as a panacea for social change and not surprisingly can generate a lot of revenue.

Philosophy for children may have become popular, but it is not without passionate criticism. For example, the UK’s Institute for Public Research proposed that all children should be taught to think critically about religious belief; but this has created the charge of relativism and indoctrination by educational and religious commentators and the press (Law 2008). It is difficult to understand this charge, but as Law argues, a proposition considered true in one religion (such as Christ is God) may be considered false in another (such as Islam); so if religious education regards all religious views as equally valid then we have an exemplar of what it means to be relativist. Philosophy for children, Law argues, can enable a criticism of relativism and need not undermine religious belief. Whereas religious dogma can brainwash the child, philosophy can provide reasons for justification in religious belief (Law 2008).

Both the UK’s Chief Rabbi Jonathan Sacks and the tabloid educational commentator Melanie Phillips blame the Enlightenment for this ‘relativism’, especially Kant, whose watchword in his short article *On Enlightenment* is *Sapere aude* (have the courage to use your own reason) and indeed there are two P4C programmes that are called Sapere and Aude (Law 2008). For Phillips and Sacks, getting children to think for themselves undermines tradition and external authority; but as Law argues, philosophy as a statutory part of the curriculum without exceptions combats the brainwashing aspects of that authority.

It is interesting to note that Kant’s battle cry of the Enlightenment was a battle cry of reason and science against the stultifying dogmas of the preceding age of feudalism. Perhaps Phillips and Sacks would like us to return to the period when scholarship became scholasticism and everyone had to accept certain dogmas on faith for fear of retribution. As Law (2008) recounted, in the late 1960s a friend was punished by a catholic school for asking why the church forbade contraception. Is this consistent with what Phillips and Sacks advocate in terms of ‘external authority’?[4]

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[4] Perhaps this whole debate concerning schoolchildren, philosophy and religious belief can be resolved if religious education and worship are thrown out of schools. Perhaps the UK should adopt the US model whereby state education excludes any form of worship and religious instruction. The school should be seen as an induction into rationality and reason to which faith and indoctrination have no place.

The book, *Philosophy in the Classroom* (Lipman et al. 1980), has become influential and well referenced. It advocated philosophical discourse for children as young as 5 years of age and stated 'if the educational process had relevance, interest, and meaning for the children, then there would be no need to *make* them learn' (Lipman et al. 1980, p. 5, emphasis given). This seems obvious, yet in England and Wales the National Curriculum and a battery of tests have left no choice but to teach to the test piecemeal bits of knowledge. It is difficult for the science teacher to develop a deep understanding if forces have to be taught one lesson and worms the next. Under the NC, mathematics has gone from mainly algebra and geometry to mainly 'data handling' and 'shape and space', as if relevance can motivate.[5] In practice the angle property of the triangle, Pythagoras' theorem or $x^\circ = 1$, for example, is given without proof as if mathematics is a question of faith – without any epistemology to show why these things are true. As Siegal (2008) argues, education without epistemology reflects a lack of respect towards children. The teachers themselves cannot be blamed because they have already been accounted by endless state inspections that specify the standard and what is expected in terms of teaching and learning outcomes.

Under such a regime P4C must seem like an oasis, its growing popularity is not surprising; but there seems to be an uncritical acceptance of its basic assumption that children are natural philosophers, but are they?

This assumption goes beyond the advocates of P4C. For example, in the novel *Sophie's World*, Sophie encounters her future mentor who points out that all young children have a sense of wonder that is lost as they get older. In P4C, Matthews (1980) argues that children are natural philosophers because they ask philosophical questions but their ability and interest in philosophy, like art, diminishes as they get older. Now while this is (seemingly) true for art, is it true for philosophy? Could every child's fascination for art simply be the motivation to develop sensory-motor skills necessary in performing such art? It seems reasonable to think of this fascination as a part of normal development, sometimes disappearing as the child matures, but philosophy may be a different matter entirely.

For the child to progress in art and for her fascination to be sustained, then she must engage with the various cultural schemata and codes that enable the art to take form (Gombrich 1960). Arguably this would apply to philosophy, but what's in doubt is the initial motivation to do philosophy. Children may have a sense of wonder which is lost through schooling, but is there any intention to be philosophical and do they expect certain criteria to be satisfied in answering their questions? Hand (2008) answers in the negative but maintains that such intention and criteria can be learnt and developed. Like art, children must engage with the various schemata of philosophy (e.g. the kind of questions to ask, such as epistemological or metaphysical, and the sort of answers to be expected) if progress is to be made and interests are to be developed in philosophy.

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[5] Although most of the mathematics of the NC supposedly reflects mathematical practice in the real world, as Noss (1997) and Dowling and Noss (1990) point out, it does not even do that.

Hand (2008) argues that there is more to being a philosopher than the asking of philosophical questions and that what is missing is the intention of pursuing a line of inquiry in accordance with the question – children lack the appropriate methods of investigation – although with the asking of such questions they can be appropriately taught how to use these methods. Matthews (1980, 2008) has criticised Piaget's deficit model which proclaims young children to be unable to think abstractly, but has Matthews overestimated the child in terms of being a natural philosopher? For Hand (2008) the various methods of philosophical investigation have to be developed.

There is much reference in the literature to Matthews' deficit model of cognitive development in Piaget. For example, according to McCall, 'If you go out in the snow without your mittens, your fingers will freeze!' (McCall 2009, p. 21) involves hypothetical reasoning and yet 3-year-olds will understand this statement. McCall states that 5-year-olds are capable of 'formal operations' in that they can reason about abstract philosophical concepts and can reconstruct the reasoning of other children. Now, without denying the child's sense of awe and wonder of the world and her interactions with it, have we gone completely the opposite way as if her cognitive abilities are adult-like? Consider the following by Lipman and colleagues:

> The rules of logic, like the rules of grammar, are acquired when children learn to speak. If a very young child understands, 'if you do that, you will get punished,' it is assumed that the child understands, 'if you don't want to get punished, I shouldn't do it.' That assumption is usually correct. Very small children, in other words, recognize that the denial of the consequent requires the denial of the antecedent. Although this is a very sophisticated piece of reasoning, children are capable of it in very early stages of their lives. (Lipman et al. 1980, p. 15)

Does the child recognise that the denial of the consequent requires the denial of the antecedent and are they capable of this very sophisticated piece of reasoning? Rather than understand 'if I don't want to get punished, I shouldn't do it', the child might instead understand 'if I don't do that, I won't get punished', meaning not to do it, especially since punishment is not desirable. *How* the child understands might be to do with the discourse and her relationship between the participants.[6] From the hundreds of papers and articles on conceptual change in science education, we find that a wide range of schoolchildren and adults tend to use fallacious reasoning when defending their intuitive ideas of scientific concepts.

In the process of learning, children perform acts of reflective thought, such as whether something has meaning, its relation to the scheme of things or the difficulties they have with the problem. Although reflective, these thoughts seem more to do with metacognition than philosophy; but it does seem likely that metacognitive thinking can be transformed into philosophical thinking if the learner is encouraged to think in the abstract. According to Vygotsky (1994) children are capable of abstract reasoning which depends on the help (or rather, the *scaffolding*) by significant others.

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[6] From a sample of adults performing a classification task, Wason (1977) shows how even adults deny the relevance of facts or contradict themselves, and how conceptual conflict can arise when the force of a contradictory assertion is denied. This implies that even adults do not acquire the rules of logic just because they speak. The Lipman and colleagues assertion is therefore unwarranted.

The point is that claims about the ability of the young (especially 5-year olds) may be overstated and exaggerated; but they do throw some light on the child's potential. That potential, as we shall see, can only be realised and developed by intervention.

In a P4C discourse children may construct a logical argument and arrive at valid conclusions, but do they become aware of the logical form of an argument or the metaphysical import of a question? Consider the following by Lipman and colleagues:

> The mathematician may insist that children begin by learning simple arithmetical operations, but the children may stagger the teacher by asking, 'what is number?' – an immensely profound metaphysical question. (Lipman et al. 1980, p. 28)

But do they mean this in a profound metaphysical way, or are they at the age when they question everything as a kind of game? Do they even have a *sense* of the metaphysical?

We must shift from the habit of regarding children's metacognitive utterances for philosophical insight.[7] Consider the following:

> This manner of upstaging the normal level of dialogue by leaping to a more general level [for example the child asking 'what is time?' or 'what is distance?'] is typical of metaphysics. Instances of other metaphysical questions your children may already have posed you (or are quietly preparing for you) are these: What's space? What's number? What's matter? What's mind? What are possibilities? What's reality? What are things? What's my identity? What are relationships? Did everything have a beginning? What's death? What's life? What's meaning? What's value? What makes questions like these particularly difficult to answer is that they involve concepts so broad that we cannot find classifications to put them in - we just cannot get a handle on them. (Lipman et al. 1980, p. 37)

It seems almost a conspiracy, children waiting to pounce with metaphysical questions, but isn't this simply a challenge to the terms that are used (especially if they come across such terms as 'matter' and 'identity')? As soon as the adult fails to provide a sensible answer (usually the first time the child asks), the child may decide to persist as a kind of game, knowing intuitively that it causes a mild form of embarrassment. The point is that we may have looked at child development through the lens of our own present development. Piaget may well have underestimated the child, but his stage theory, flawed though it is, rests upon the premise that children are not little adults. The child is not a prototype of an adult whose thoughts are merely refined as she grows up – she has her own way of thinking and looking at the world. Rather than springing forth from some kind of philosophical awareness, a child's philosophical questions may be no more than the metacognitive awareness

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[7] According to Vygotsky (1987), concepts are not absorbed ready-made by the child but undergo a process of development. Initially, the concept may begin as a complex; for example, the child might use 'dog' not as a member of 'animal' but as an 'associative complex' extended to inanimate objects with fur. A complex often relies on perceptual features. For example, children who think in complexes may successfully complete a classification problem involving geometrical shapes, so the child might appear to think in concepts – until the child attempts a borderline example, such as a trapezium looking very much like a parallelogram, in which the child classifies as a parallelogram without thinking of how a parallelogram is defined (see Vygotsky 1987). The point being the child might not even think in concepts, let alone concepts that may be deemed philosophical.

that adults have great difficulty in answering such questions. With adult supervision, however, it is possible for metacognitive awareness to be transformed into philosophy.

The question is not how we can stimulate their challenge, apparently that challenge is ever present, but how we can challenge them. That challenge is necessary if we are to be certain what the child is driving at. What children mean should not be taken at face value, but as soon as a discourse opens up as to what they mean, we then have an educational situation in which understanding and meanings emerge and change. Intervention is necessary if what the child says is not to be overestimated, bearing in mind that what the child says during the intervention does not necessarily reflect any initial cognitive state or disposition.

What seems promising is the realist philosophy of McCall's CoPI (the Community of Philosophical Inquiry), which asserts that someone can be wrong and contrasts with the P4C Deweyan pragmatic philosophy that truth is constructed and negotiated (McCall 2009, see p. 81). What makes CoPI *essentially* different to all the other approaches such as the Nelson Socratic Method or the various P4C programmes such as Sapere and Aude is its realism:

> The external realist philosophy which underlies CoPI holds that immaterial creations of human beings such as language, concepts, theories, symbols and social institutions, while owing their origins to humans, once made, then exist independently. We can be wrong about them too. (McCall 2009, p. 83)

Perhaps the essential ingredient in any philosophical discourse concerning science and mathematics with children is the view that scientific concepts and laws may be considered to exist in what Popper calls the World Three of the objective content of thought, with discussion as to what existence means here. Are scientific concepts and laws idiosyncratic, are they true because scientists believe in them, are they indubitable facts derived from observation? Any such opinion may be expressed by children who are used to this kind of discourse, and the teacher can always put into perspective that opinion with respect to World Three, bearing in mind that any such opinion opens up a whole world of discourse concerning such issues as Platonism, fallibilism, method, methodology, ontology, epistemology, abstraction and validity.

McCall gives a list of what the CoPI Chair needs to know in order to recognise the various philosophical theories and assumptions that underlie everyday discourse (which contrasts with the view that the teacher does not need to know any philosophy, only the way children learn, e.g. the Primary Teacher Update article by Lenton and Videon (2011)). For the philosophy of science, the list recommends the teacher becoming aware of such things as induction, deduction, falsification and paradigms. Hopefully such a teacher will enable the class to also become aware of such categories in their discourse. Unfortunately, though, there is nothing by McCall on philosophy connected with mathematics.

The section after next is a presentation of how the mathematics teacher can introduce philosophy explicitly in her teaching of mathematics. This is perhaps unique in that many articles on school mathematics with philosophical discourse tend to separate the very learning of mathematics with the discourse, and this is reviewed next.

22.3 A Review of Philosophy in the Mathematics Classroom

There is very little on philosophy in the mathematics classroom, it tends to be implicit in the overall view of the P4C programme. In *Teaching Children to Think* by Robert Fisher (2005), there is reference to Skemp's relational and instrumental understanding in mathematics education but nothing in terms of philosophical discourse and mathematics, despite a chapter on philosophy for children and chapters on creative and critical thinking, With reference to such things as 'shape and space' and 'data handling' of the National Curriculum, however, the book tries to encourage thinking skills and the understanding of how the various mathematical concepts relate to each other, but it has missed the opportunity to use philosophy explicitly as an aid in understanding those concepts. Fisher might reply that he is hamstrung by the NC.

Kennedy (2007), however, connects philosophy with understanding mathematical concepts while also referring to metacognition and creativity. She discusses how a classroom community of mathematical inquiry can become a community of philosophical inquiry by discussing various mathematical problems. She contrasts the transmission model of teaching with the constructivist classroom through which sense-making occurs as a collaborative endeavour. The method is the P4C programme with its participative, dialogical and egalitarian emphasis and states that similar to this have been the works of such metacognitive greats as Schoenfeld (1989) and Goos (2004). The problem here is that there has been a tendency to encourage either metacognitive or philosophical thinking after the content of the mathematics has been learnt, such as solving an integral in a metacognitive way (Schoenfeld 1989) or solving a projectile problem in an investigational way (Goos 2004). How was the content, such as integration or projectiles, learnt in the first place (see Rowlands 2009)?

Nevertheless the article shows a way in which meanings can be constructed in discussing the concepts of ordinary school mathematics philosophically, such as asking 'When can we say that we 'understand' a mathematical concept?'… 'How can we trust in math that is not experienced?' (Kennedy 2007, p. 6). Kennedy sees this as complementing concrete mathematical investigations. Perhaps for the first time, we are seeing a greater integration between philosophy and mathematics in the classroom, but the integration is not complete. Although one complements the other, they are still separate. The question arises: How can we teach mathematics in a philosophical way that doesn't entail teaching the mathematics first prior to any philosophical considerations?

The rest of the article is taken up with examples of discourse in action by showing parts of the transcript concerning two problems. The first is the problem of a frog at the bottom of a 30 ft well. Each hour it climbs 3 ft but slips back 2 ft. How long will it take to get out? The second problem is: given the two infinite sets $\{1, 2, 3, 4, 5,\ldots\}$ and $\{2, 4, 6, 8, 10,\ldots\}$, do both sets have an equal or a different number of elements? The discourse is of a very high standard and like all the examples of this kind (such as in Lipman and colleagues), it is surprising to know these are the conversations of upper primary/elementary children. We are told in each case that the children have already engaged in a community of philosophy for many hours beforehand,

and we get the sense that all this is possible, although we are not told whether the children involved were high developers. We also have to bear in mind that what we see is presumably only part of the many hours of transcript recorded. Nevertheless the conversations seem very mature for primary (elementary) schoolchildren and appear encouraging.

If the class can arrive at the conclusions as presented in the scripts, then this remarkable accomplishment ought to be encouraged, but what if the conversation comes to an impasse, or is a non-starter or the class arrives at a conclusion that is wrong? Must everything be constructed by the class or can/should the teacher give a clue, a hint, or indeed a correct answer? With the first example the class arrived at just how ambiguous the question is (a child says, quite late on in the discussion 'Well that's the way we understood it, but it's not quite clear'. p. 10) – they did the task – but couldn't the teacher point out the ambiguity? In the second example the discussion repeated itself until someone asked the question 'is infinity a number?' which created a new lead. What if no one asked that question? Of course the teacher could always ask such a question to keep the discourse going, but we have to bear in mind that the teacher, under such a programme, must not direct the discourse to arrive at preconceived ideas. There is a sense in which the discourse is directed by the children, and this is perhaps the greatest weakness of the programme.

Despite its criticisms of Piagetian stage theory, the programme itself is quite Piagetian in the sense that the children must find out for themselves rather than being told, although surely a hint here and there is more appropriate than spending a whole lesson trying to fathom the ambiguity of a question. In real life perhaps the problem would be rejected out of hand because of its ambiguity.

The many examples of classroom philosophical discussion in the literature are outstanding in their complexity, abstraction and logic; but we are not given the background of the chosen samples or details of the methodology, and we are not sure of the amount of transcript that is not included. The major problem seems to be the notion that it is OK for children to pursue a path of discussion that leads to nowhere or that they are neither right nor wrong. Of course, some paths do achieve an undecided position, such as the concept of infinity in De la Garza et al. (2000) classroom discussion,[8] but that is because of the nature of the concept under discussion. In general, the teacher should direct the class to the target concept. Hand (2008) criticises the widespread view that philosophy has no right answers by showing that all philosophical questions presuppose answers that are right, despite some questions as yet having no right answers. It is up to the teacher to convince why a particular answer is right (or wrong).

Although a philosophical question presupposes a right answer, the answer may be so formal that it may be inappropriate for secondary school pupils to entertain the

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[8] 'Many [children] found convincing a view which could well be labelled constructivist – that infinity is not something we imagined as complete, but was a result of the fact that there was no stopping point, that infinity just kept going on. We then turned to measuring infinity and, having detoured through Cantor's proof that the number of integers was equivalent to the number of even integers, ended on a note of indecision' (De la Garza et al. 2000).

question. Nevertheless certain questions that have rigorous formal answers appropriate for undergraduates may have educational value for secondary school pupils. Certain answers lacking in rigour may be appropriate to schoolchildren because they expose or contextualise relevant concepts to be taught or provide a satisfactory ‘completeness’ to the question. Certain paradoxes may not have an answer, but for years may stimulate members of the class to think of one. Although questions presuppose answers, there may be more than one answer. The teacher must consider the educational value of her questions and the kind of answers to arrive at.

Daniel and colleagues (2000) present a research report of an ongoing project to implement a community of enquiry in the mathematics classroom. The article is essentially an argument for why a community of discourse is necessary for the mathematics classroom as opposed to the lack of meaningfulness of the mathematics taught in a traditional classroom. It discusses the myths and prejudices surrounding mathematics and philosophy (that there is only one way of getting the right answer or that philosophy isn’t for children, etc. similar to the Primary Teachers Update article by Lenton and Videon (2011)) but seems to propose that the meaningfulness of a community of enquiry can only be accomplished if the mathematics is related to the everyday experiences of the child. For example:

> Dewey states that as soon as studies in mathematics are dissociated from personal interest and their social utility, that is, when mathematics are presented as a mass of technical relationships and formulas, they become abstract and vain for students. It is only when children become intrinsically interested and conscious of mathematics as a means of solving daily problems (as opposed to end in themselves), that they enjoy playing with numbers, symbols and formulas. (Daniel et al. 2000, p. 5)

Why does developing an intrinsic interest involve the solving of daily problems? Presumably Euclidean geometry, which is an end in itself and can be unrelated to practical problems, will not do here. Like most communities of enquiry, an ‘everyday’ story is presented and a list of mathematical/philosophical questions (involving such concepts as truth, proof and infinity) are asked and pursued. The story seems to be the ‘everyday’ from which abstract problems arise – but this is not ‘mathematics as a means of solving daily problems’ as stated by Daniel and colleagues (2000). As this is an ongoing project, no results are discussed, although a summary of the results of a teacher questionnaire is stated. According to the teachers, some of the students reported that relating the discussion to mathematics wasn’t much fun and that sometimes they don’t want to hear about mathematics. Nevertheless they took well to the discourse. What is interesting is that they are not used to this kind of discussion involving mathematics.

Outside of the P4C programme, Prediger (2007) argues that philosophical reflections must play a prominent role in the learning process if an adequate understanding of mathematics is to be achieved by the class. By philosophical reflections she does not mean reflecting on classical philosophical theories, but reflecting on the mathematical activity itself, expressed by the verb *philosophize.*

What will be presented in the next section is an argument for philosophy to be integrated with a cultural-historical approach to teaching mathematics in order to engage children, for children to understand the nature of the concepts that they are expected to learn and to situate these concepts in the society that they belong. However, philosophy without the history (or perhaps with a little history) of mathematics can still be value-added, and this is discussed next.

22.4 A New Emphasis on Philosophy in the Mathematics Classroom

Philosophy without (or with little) history may seem a little empty, but it can have an add-on effect. The philosophy may only be related to the mathematical issue at hand (e.g. the concept of limit by dividing a circle into equal sectors and rearranging them to form a parallelogram of sorts – the notion of infinity explored by considering an ever-increasing number of sectors in the proof of $A = \pi r^2$), but much of what is taught can be done in a philosophical manner, such as the Socratic method of asking conceptual questions, parallel questions, contradictions, conjectures and counterexamples. The teacher orchestrates the class towards the target concept (or each target concept in succession), and philosophy provides the opportunity for exploration into the concepts to be learnt.

This is what Jankvist (2012) characterises as the *illumination approach* whereby the philosophy supplements the mathematics, although Jankvist's *philosophical discussion approach* (whereby groups of students enter debate concerning philosophical issues such as whether mathematics is discovered or invented) can also be included.[9] Using Jankvist's taxonomy, this is philosophy as a *means* rather than as an *end*. Similar to Jankvist, however, it will be argued that it would be more advantageous educationally if that philosophy was concerned with the history of mathematics. Meanwhile we shall look at various examples of philosophy and mathematics that can be introduced to the classroom but without, or with a minimal, history.

As an example of value-added philosophy, consider the paradox of Gabriel's horn (or the wizard's hat) that is asymptotic. A surface is generated by the 360° rotation about the x-axis of the curve of the function $f(x) = 1/x$ for $x \quad 1$ (Fig. 22.1).

This has a fixed volume (π cubic units) but an infinite area (see Clegg 2003). How is it possible for a finite volume to be enclosed by an infinite surface area (Clegg states that he has yet to see a satisfactory explanation)? After the calculus of basic volumes and surface areas have been learnt, such a question posed can raise discussion as to what volume, surface area and limiting case actually mean (it may be worth considering a cross-section perpendicular to the x-axis: a circle of radius r in which $r = f(x)$, followed by the rate in which the circumference decreases compared to the rate in which the area decreases, with respect to r. Similarly, by considering x the rate in which the surface area decreases can be compared to the rate in which the volume decreases, with respect to r). This can be a good prerequisite for fractals

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[9] This is not, however, an instructional unit on philosophy and mathematics (Jankvist's *modules approach*) nor is it a course that pursues a particular philosophy of mathematics (Jankvist's *philosophy approach*).

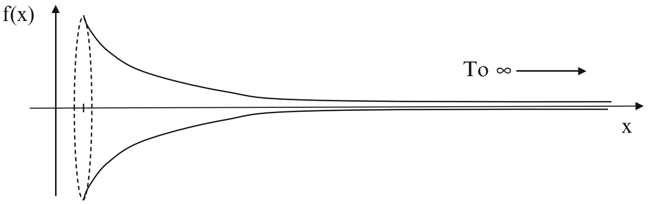
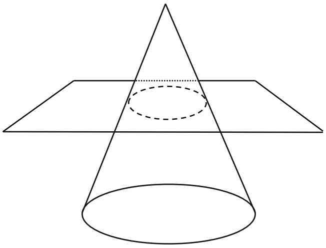


Fig. 22.1 Gabriel's horn (or the wizard's hat) – finite volume, infinite surface area

Fig. 22.2 A right-cone cut by a plane parallel to its base – are the two *dotted circles* (shown as one *dotted circle*) equal or unequal?



such as the Koch snowflake that has finite area but infinite perimeter, or the Sierpinski carpet which has zero area but has a non-empty interior – all of which can be discussed meaningfully prior to or without the formalism.

If a cone is cut by a plane parallel to its base, are the two circles formed out of the cut the same or different (although this can be introduced without reference to history, in fact it came from the Ancient Greeks) (Fig. 22.2)?

If the same, then we have a cylinder; if different, then the surface would not be as smooth as it is. This example, like many others, lends itself to the many ways in which the teacher can direct the discussion (e.g. 'my friend has an electron microscope and she didn't find any cone to be made of cylinders. What do you make of that?'). This paradox may not only create cognitive conflict, which some regard as essential in cognitive development, but lends itself to the ideas of a limit (the thickness of a cylinder having zero limiting length).[10]

Another example is Galileo's wheel paradox: the wheel fixed within a wheel (see Clegg 2003) (Fig. 22.3).

In one revolution the smaller wheel has travelled the same distance as the larger wheel, so it must have rolled more than one revolution, which is absurd. Although this paradox can be presented ahistorically, nevertheless historical considerations can always serve to illuminate. For example, consider, as Galileo does in his *Dialogue on the Two Principal World Systems,* two concentric octagons as shown (Fig. 22.4).

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[10] Of course a little historical excursion can reveal how the Sophists used indivisibles and how the school allied to Plato used Eudoxus' method of exhaustion. The two can be compared in Archimedes's various proofs for the quadrature of the parabola (and the *Palimpsest*, the book where Archimedes uses indivisibles, has itself a wonderful history).

Fig. 22.3 A wheel fixed within a wheel and concentric

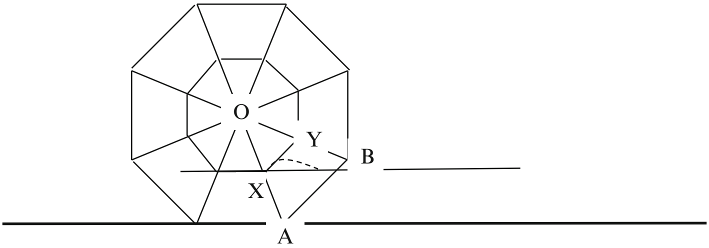

Fig. 22.4 Representing the circular wheels as octagons

In a one-eighth turn of the larger octagon, triangle OAB has been rotated 45° clockwise about a stationary point A. However, line XY has not only rotated 45° clockwise as well, but the point X about which XY has rotated has itself moved along the arc of a circle as shown. As Clegg states, side XY is lifted off the track.

The paradox is that with two concentric circles, there is sense in which no point on the smaller circle has left the track, yet in one revolution, a point on the smaller circle has traversed pi times the diameter of the larger circle, not the smaller. Of course, no point on the smaller circle will stay on the track, the loci being a cycloid that is smaller in height compared with the cycloid of a point on the larger circle; but we have to account for the horizontal displacement. Galileo (as Salviati) considers two concentric regular polygons of 100,000 sides in which after one turn the smaller polygon has traversed 100,000 smaller sides plus 100,000 tiny gaps between each side (we still have the isosceles triangle OAB, but with a much smaller AB, in which the 'tiny gap' is XY lifted off the track). One educational value of this example (and one that is stated by Clegg 2003) is that we can see Galileo tackle the complexity of the number of sides increasing towards infinity with the number of 'tiny gaps' also increasing to infinity but with the 'gaps' decreasing to zero.

Unfortunately Galileo does not solve the paradox, which was transformed into the definition of infinity by Dedekind and became solvable when presented in the new context of sets around 1870. Set theory is very abstract, so presenting the paradox to schoolchildren does not mean that they will eventually see the solution, but they can see the problem and the way Galileo tackled it.

Do complex numbers really exist? It is perhaps surprising that many websites state categorically that they do *really* exist (rather than just *assume* they exist). Some websites justify the assertion by referring to the very successful applications of complex numbers; but does success necessarily imply existence (certainly not for the relativist)? Complex numbers are counterintuitive, yet they are usually introduced in a matter of minutes, justified with reference to the complex roots of a quadratic and followed by its algebra in the hope that students will subsequently appreciate what they are through their applications. Philosophical discourse could make intelligible something that is counterintuitive, such as whether it is a question of existence or formalism (e.g. is the formalism reduced to $a+ib=c+id$, with $i^2=-1$, implies $a=c$ and $b=d$?). Of course, a little history (such as the reluctance of many mathematicians, from the Renaissance to the nineteenth century, to accept complex numbers) can put into context for the students their difficulties with complex numbers, especially since these difficulties plagued the best minds.

Is there a smallest number after 0? This question can be asked across the range from schoolchildren to undergraduates with the discourse appropriate to the level of development already attained. For example, schoolchildren could be introduced to the paradox of a 'next' number having an infinite number of decimal places.

Certain topics can be discussed in a philosophical manner even though the discussion may not be philosophical. For example, if $a^n=b^m$, when can we say $a=b$? What values of x and n satisfy $x^n=1$?

Philosophical discourse can also highlight the aesthetics and 'divinity' of mathematics; for example: Is Euler's equation ($e^{i\pi}+1=0$) evidence for the existence of God? Surely the coming together of the five most important numbers reveals divinity? How is it possible for a particular irrational number, raised to the power of a particular irrational number times i, to equal -1?

If $y=f(x)$ enables us to map x onto y, what can we make of dy/dx? A function is defined in terms of the way it maps the elements in the domain to the elements in the range – it can be said that a function is a *process* – so how come it is an object that can be differentiated? It would be worthwhile looking up David Tall's notion of *procept* (e.g. Tall and Gray 1994), even though this is for educators rather than for children.

How does the circumference of a circle relate to the area changing with respect to the radius? How does the surface area of a sphere relate to the volume changing with respect to the radius?

Many of these discussions are about mathematical paradoxes and can always make the subject more interesting than it already is (and pupils will always encourage it, even if to delay pencil and paper exercises). Skilful use will encourage a deep understanding of the concepts involved, something that Fisher (2005) refers to in terms of Skemp's relational and instrumental understanding; and the formalism can wait until the appropriate level of development. Such philosophy can either be an add-on ('bolt-on'), such as the wizard's hat, or it can be integrated into the introduction of a mathematical concept, such as complex numbers. Either way, it is value-added.

Of course, certain ground rules have to be maintained, such as not to ridicule anyone's contribution, not to hog the limelight (and try not to avoid it either). Initially more rules and a stricter regime may have to be enforced (e.g. 'hands up rather than call out'), but most likely it will become more relaxed and informal, everyone behaving in a respectful manner towards everyone else and the discourse. Most of the time the teacher should be at the front, rather in the traditional manner (and, incidentally, the pupils should perhaps sit in rows facing the front). The teacher *is* the sage on the stage, consciously directing the discourse towards fixed aims (although the discourse may be such that she allows it to go its own course without intervention) with preconceived ideas as to what she wants her class to arrive at. There has to be a target concept. This is not brainwashing, nor is it getting pupils to believe what she believes without realising it. It is teaching mathematics but with a little philosophy directed by the teacher – in the discourse she gives reasons for why something is the case and this can always and hopefully will be challenged. This is philosophy in the mathematics classroom with the teacher facing the class (sage on stage) most of the time (allowing for debate and the conversation going its own way), included in normal mathematics classes 5 h a week, versus philosophical discourse around a circle or horseshoe (a metaphor of the guide on the side) usually timetabled for 1 h a week.

The main proposal of this chapter is more than philosophy as a bolt-on; it is the teaching of mathematics with philosophical considerations but also within a cultural-historical perspective. Such a perspective will enable pupils to see and learn the great transformative events in the history of mathematics that transformed culture as well as cognition.

The main proposal is consistent with Jankvist's (2012) integration of history and philosophy in the teaching and learning of mathematics. The history is akin to Jankvist's *illumination approaches* that 'spice up' the mathematics within the historical context; and although not incompatible, this has less to do with the *modular approach* that is devoted to history or the *history-based approaches* that investigate a development of mathematics. The main proposal has more to do with history as a means rather than as an end, and although the use of original sources can serve a purpose, the history is primarily concerned with the transformative events that transformed cognition and culture as well as the mathematics. This is history to serve the understanding of the mathematics and to place the mathematics in context. Perhaps with certain exceptions such as Greek geometry, the history is not *necessarily* to understand the mathematics as constructed and perceived at the time. The history can have a place in understanding past developments from the standpoint of today – provided any historical specificity is not lost through a whiggish interpretation.

Although these transformative events may be considered 'epistemological obstacles' for both pupils and the mathematicians of the time, the proposal is not based on the recapitulation theory that historical obstacles parallel the difficulties that pupils have. This is simply because the obstacles to be raised will most likely be qualitatively different to the obstacles of the time, represented by the difference in notation. Nevertheless certain historical obstacles may be chosen to engage the class with the difficulties pertinent to understanding the relevant mathematics and, just as important, to see how this mathematics transformed cognition as well as culture. It also shows how the relevant concepts were hard-won, something that pupils can identify with in terms of their own difficulties.

Consider abstraction and proof, the two transformative events that occurred simultaneously, which transformed mathematics from an empirical affair to a science of reason that not only transformed Greek society at the time (see Kline 1972) but eventually led to the scientific revolution and the technological society we know today. For over two millennia, classical geometry served as a major rite of passage into scientific culture, as a world view, as a conceptual lens and as the introduction to rationality. From Thales to Euclid, classical geometry expanded into a world of abstract, formalized, theoretical objects and purely intellectual processes. Initially children are given a story of how Thales learnt the practical geometry of the Egyptians, a geometry borne out of the annual flooding of the Nile, and how he abstracted the notion of the geometric straight-line from observing stretched rope. They can then go outside with clipboard and paper and draw two intersecting ropes in six stages of abstraction leading to the platonic form of two intersecting lines (see Carson and Rowlands 2007; Rowlands 2010). The class is made aware that what we know about Thales is second-hand, written by Greek historians and commentators (Eudemus, Aristotle, Proclus) centuries after the event, so we don't actually know how Thales performed the abstraction necessary to have created the theoretical objects of geometry. He is credited for the very first five proofs which may not have been possible without the construction of added lines, which suggests that he did undergo some form of abstraction.

The point is the emphasis on this remarkable 'event' itself (if it was an event) that changed the course of the history of mathematics and indeed culture itself. This is not history as an examination of what actually happened because we only know what happened second-hand centuries after the event. Thales becomes a narrative device in contextualising what would otherwise be purely formal and symbolic, and although historical detail whenever possible is extremely important, it is more Thales the myth than the actual historical figure itself.[11]

During each stage of abstraction, the teacher asks what abstraction means, what has been left behind and what has been taken forward during each stage and introduces Thales' attempt to demonstrate that opposite angles of two intersecting lines are equal, despite the fact that it is obvious that they are equal. The class is not given a proof, but constructs a proof under the guidance of the teacher who is careful not to give information explicitly (see Rowlands 2010), although information is conveyed implicitly through the asking of questions. During the fourth level of abstraction (*personal concept*), the class is invited to close their eyes and think of two intersecting lines, to think of what has been taken forward and what has been left behind and how this differs to their previous drawings of two intersecting lines (the *literal representation* and the *abstract representation*). At the fifth level, the class considers the concept of two intersecting lines as it appears in textbooks (the *authorised concept*). At the sixth level (*platonic form),* the class is introduced to the platonic form of two lines intersecting and asked where the truth of opposite angles being

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[11] At the secondary level the aim has more to do with developing an understanding of mathematics itself (and its place in terms of impact) than it has with understanding its history. The same with philosophy; for example, a secondary school mathematics teacher doesn't raise Plato's distinction between knowledge and belief because it happens to be a good thing to know, but because it illuminates the concept of proof.

equal resides. As part of the course, the pupils can be introduced to other Forms, such as Virtue or Shape, and to see how Socrates rejects given examples of a Form in favour of it being well defined.

Care should be taken, however, not to present these ideas as true. Arguably (and similar to the sophists), there is no Form of Justice or Virtue, and these concepts do not transcend cultural boundaries; but the Forms can be contextualised by emphasising the Forms as representing abstract objects that could have easily disappeared, leaving the world to concrete exemplars. Subsequently the class can then learn the basics of Greek deductive geometry with the opportunity to discuss wider philosophical issues such as whether mathematics is invented or discovered and the immortality of the soul (similar to Plato's *Meno,* the class who has constructed a proof but without the teacher giving information can question where their knowledge and understanding comes from). During this process the class can become aware of the theoretical objects of geometry (the point as a dimensionless object, the straight-line as having only one dimension, the circle both as an object and as the locus of a moving point, a fixed distance from a fixed point, the plane having no thickness, etc.) that they are normally expected to use in a traditional lesson but ordinarily have no idea as to what these objects are. The cultural aspect includes how the geometry transformed Greek society (art and architecture, philosophy, law, etc.; see Kline 1972) and how our modern technological society evolved from this (the scientific revolution of the 1600s would not have been possible without the abstraction and idealisation of Greek geometry).

Thales is not only credited as the first Greek geometer but also the first Western natural philosopher, who tried to explain the world without reference to divine will or intervention. According to Aristotle's *Metaphysics*, Thales maintained that water is the 'material principle' of the world from which everything is made (see Barnes 1987). Geometry and philosophy grew up together, culminating in Plato's famous statement at the entrance to his Academy ('He who is ignorant of geometry should not enter here'). This is not surprising if you regard geometry and philosophy as somehow having similar levels of abstraction – something that can be discussed with the class.

It is hard to imagine a discourse on proof with very little reference to philosophy, yet if proof is taught, then it is seemingly done so with little regard as to its nature. Proof is often a means to an end, an accomplishment of a task, yet there is little reference to what it is or just how important it is.[12] According to Kunimune et al. (2009), there are many Japanese children who are capable of Euclidean proof who do not see the importance of deductive proof over inductive procedures. This is perhaps common wherever deductive proof is taught, but it is odd that children can perform proof without acknowledging its importance and relevance.

Get a class who can use the protractor to each draw their own triangle and then to measure the angles. Record their answers. Here we have a whole new universe of

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[12] And as far as the majority of English and Welsh classrooms are concerned, proof no longer exists and perhaps because many teachers and curriculum designers can remember the negative experience of having to regurgitate proof in examinations. For some educationalists, proof means rote learning.

discourse opening up – from the student unwilling to believe that the angles add up to 180° because hers add up to 181° (a problem for the radical constructivist) to whether the measurements of a million students would be enough to justify the angle property – leading hopefully towards a formal proof. If appropriate, the teacher could introduce Bertrand Russell's good inductivist turkey (ever since it could remember, it was fed breakfast at 9.00 a.m., but decided not to be certain that it would be fed at 9.00 a.m. the next day until it amassed enough evidence. After the days, weeks and months went by, it decided that it could be certain; but the next day was Christmas, and rather than having breakfast at 9.00 a.m. had its throat slit (Chalmers 1982)) and compare inductive procedures with deductive proof with specific reference to the triangle. Given their sense of wonder and their abilities, it is possible to engage children with the concept of proof, especially from a philosophical approach that encourages them to express what they think on the subject, freely and without any fear of giving a wrong answer. Eventually, they will expect epistemological reasons for why something is the case or why they have to learn it, giving them a critical edge to their learning.

Iversen (2009) suggests the comparison of proofs in both mathematics and philosophy as well as the comparison of other similar concepts in both domains as a way of developing a cross-curricular competence of mathematics. Now if this was done in a historical-cultural way so as to show the impact of the *Elements* and proof in particular on society (e.g. Spinoza's *Ethics* and Newton's *Principia* in the Euclidean deductive style, the ideas of proof and deduction in law to even the self-evident truths of the American Declaration as axioms), then it can be shown how proof impacted philosophy, especially since they grew up together for 300 years. Unfortunately the suggested St. Anselm's ontological proof for the existence of God (essentially: perfection must involve existence) is a very poor example.

Unlike perfection, existence cannot be predicated and so this seeming 'proof' compares badly with, say, the proof of the angle property of the plane triangle.

Philosophy has so much more to offer. Why not engage students with the notion of proof in conjunction with Plato's distinction between knowledge and belief as a backdrop? For belief to become knowledge, it has to be shown why the belief is true. Showing why becomes the anchor for certainty and proof can be seen as the highest warrant for certainty, with the notion of fallibility brought in to discuss the context in which we can say a mathematical proposition is true. Proof is perhaps the highest form of human achievement concerning justification[13] – so philosophy ought to be used to bring out the role of proof as a stunning advance in human ingenuity – it would be a pity if philosophy was merely 'compared' with mathematics in the sense of both having similar ('cross-curricular') notions, such as proof, only to find that some of those notions aren't so similar after all (such as St. Anselm versus Euclid).

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[13] Even social constructivists such as Paul Ernest love and rely on Godel's proof, even though they don't like proofs in general (Ernest goes so far as to regard proof as Eurocentric and its glorification racist). This and other social constructivist contradictions can be found in Rowlands et al. (2010).

Just as history and philosophy have a very important role in science education (an exemplar being Michael R. Matthews' International Pendulum Project), so history plays a very important role in discussing philosophy in the mathematics classroom. The transformative leaps in the history of mathematics, such as Thales' abstraction from concrete exemplars to theoretical objects and his beginnings of what was to become deductive proof, provide the basis for understanding the terms of discourse and how these theoretical objects relate conceptually. This can be achieved with almost any level of development, and there is evidence to show the possibility (see Rowlands 2010), not only with high achievers but more importantly with low developers as well.

With no doubt the exclusion of rigorous foundationalist issues such as logicism, formalism and intuitionism, the nature of mathematics can be discussed in terms, for example, of platonic ideals and whether or not mathematics is invented or discovered (see Rowlands and Davies 2006). This is not teaching philosophy per se, but using philosophy to enhance a deeper understanding of the mathematical concepts involved, for example, the concept of infinity regarding the proof for the area of a circle, the finite sum of a converging infinite series (which can be related to an adaptation of one of Zeno's paradoxes) or the derivative. Berkeley's criticism of the derivative as the 'ghost of departing quantities' can be useful here.

The most important emphasis, however, has to be the philosophical consideration of the transformative leaps that have occurred in the history of mathematics, such as the advent of symbols, lines-rays-segments-angles-triangles; constructions; the circle as a mathematical concept; the advent of formal proof; infinity and the relationship between algebra and geometry (see Carson and Rowlands 2007). There were three major overarching transformations in the history of mathematics: Greek geometry leading to the axiomatic form of the *Elements*; the ideas of the seventeenth century that culminated in the works on calculus by Newton and Leibniz (perhaps this would not have happened if Hindu and Moslem developments had not reached Europe) and the rewriting of mathematics in axiomatic form in the nineteenth century followed by the 'rebirth' of mathematics under Riemann, Dedekind, Cantor and Hilbert. Perhaps the second ought to be left until the pupils reach at least 16/17 years of age and perhaps the third ought to be left until university, but the first gives ample scope for philosophical discourse at the secondary level without the demands for rigour. The concept of irrational number, for example, can be introduced in terms of the Pythagoreans describing the world in terms of number and their discovery that the diagonal of a square cannot be measured exactly (with auxiliary issues such as killing for love, out of vengeance, for country, on the one hand, and killing for squealing that $\sqrt{2}$ is irrational, on the other). A formal theory of the real numbers is not necessary at this level.

Whatever the emphasis on philosophy, however, the overall emphasis has to be on the metatheory of the mathematical concepts to be taught, such as the nature of the concept and its place within a system of concepts, its impact in terms of that system and its impact cognitively and socioculturally.

Philosophy presupposes answers that are either right and wrong, that answerability is a necessary feature of questions and philosophical inquiry is not a futile quest into questions that have no right or wrong answers (Hand 2008); and this is particularly the case when the philosophy discusses mathematical concepts, but children ought to engage in mathematics with philosophy but without the fear that their answers may be wrong. Here metacognitive skills may be enhanced as pupils try to relate their understanding to the cognitive demands of the course (and making public without fear of ridicule).

Perhaps more importantly, however, is that philosophy and mathematics can encourage creativity in Boden's (1994) transformative sense, for example, by giving the freedom to explore the dropping of some of the constraints of the subject, such as dropping Euclid's fifth axiom (the parallel postulate) to see whether the angle property of the triangle still holds prior to triangles drawn on spheres. Mathematics and philosophy within a cultural-historical context provides the opportunity to explore the creativity involved in such transformative leaps that changed cognition and culture. Students will begin to see creativity as a human endeavour to which they belong, especially if they appreciate the cultural-historical significance of fundamental concepts, their cognitive impact and just how hard-won they were. Creativity in Boden's transformative sense requires both learning the subject to exhaustion and having the freedom to play at a meta-level (see Rowlands 2011). That meta-level can be attained with the use of philosophy, especially from an historical-cultural perspective.

22.5 Conclusion

Hopefully it has become evident that what is being proposed is far removed from the philosophy for children programme: the teacher will always have preconceived ideas as to what she wants her class to know and understand. But this is not the imposition of the teacher's views upon the class. The imposition is the mathematics, but the teacher will hopefully develop the critical state of mind that challenges what is considered true in mathematics and hopefully develop the ability to become creative within mathematics.

The aim of this chapter is not to disparage the philosophy for children programme, although what is being proposed is quite a radical departure from that programme. Nor does it mean a radical overhaul of the traditional classroom. Mathematics is still taught but with the encouragement of becoming critical, that nothing is given on faith and that what is taught becomes part of the heritage that children belong and have the right to become enculturated. It is about the learning of mathematics that has become the fabric of today's technological society but with a comprehension and a critical stance that can encourage the child to become a discerning citizen of that society. Such an approach outlined above not only has the potential to enhance metacognition but creativity as well, not in the sense of novelty but in the sense of transforming the subject. Only then will mathematics be truly owned by all children.

When truly owned, then perhaps more students will be taking a mathematics degree at university, and perhaps the lectures will be similar to the ideal Socratic discourse of Lakatos' *Proofs and Refutations*. In Proof and Refutations the teacher leads the discussion with (admittedly) very bright students; but this may be possible with all students of varying levels of development if the mathematics has already been introduced philosophically, as a Socratic discourse, at the secondary school level. Lakatos' Socratic discourse is the ideal to which we can aspire – in our own classrooms and hopefully, 1 day, to the next level of learning/teaching mathematics that encompasses this ideal.

What has been proposed is only possible if student teachers are trained in introducing philosophy to the mathematics classroom, trained not only in raising philosophical questions concerning the mathematics taught but also in terms of establishing the classroom norms for the discourse to take place. Philosophy as well as history should be mandatory in mathematics teacher training. Not necessarily philosophy and history per se, but as aids in the teaching of mathematics.

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Chapter 23
A Role for Quasi-Empiricism in Mathematics Education

Eduard Glas

23.1 Introduction

In modern philosophy of science, there is virtually no disagreement about the fallibility of empirical scientific knowledge. We just cannot be absolutely sure that a scientific theory will stand up to all future tests. Mathematical propositions, on the other hand, do not refer directly to matters of empirical fact and therefore look like products of pure thought, immune to empirical refutation. They seemingly possess the absolute certainty of analytic statements or logical truths.

This view of the matter has had a strong impact on the public image of mathematics and, in particular, on the way in which teachers and their pupils regard the mathematics taught in school. They still often look upon mathematics as the one teaching subject where practical experiences are irrelevant and where there are single right answers to all questions, whose correctness is beyond all doubt. Is a different view at all possible?

Although it is true that mathematical propositions are not straightforwardly empirically falsifiable, they are not immune to all (other) forms of criticism. They may, for example, be criticised for failing to solve the problem which they were designed to solve. In science, too, deficiencies in problem solving or explanatory potential are normally counted as negative evidence. So in this respect, mathematics is not unique and not as radically different from science as those who entertain the above view suppose.

Throughout this chapter, extensive use has been made of previous articles mentioned in the references.

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Especially the most advanced sciences are very much like mathematics in that their conceptual apparatus and organisation are to a large extent non-observational and self-supporting. Only think of the theory of relativity, which depended on the nonempirical principle of relativity and the non-Euclidean geometries developed in the second half of the nineteenth century. Einstein's achievements relied on thought-experiments and mathematics; empirical methods became relevant only when confirmation or corroboration was called for. More recently, the fruitful interaction between string theory and differential geometry has even led to a reversal of the direction of influence: mathematical physicists constantly reveal new mathematical structures undreamt of before.

The derivation from scientific theories of empirically testable consequences may require considerable theoretical effort, and their confrontation with observational material is itself dependent on theoretical assumptions about the meaning of terms, the interpretation of observations, theories of experimental design and procedure, ceteris paribus clauses, etc., briefly: on more basic theories. Testing a scientific theory therefore ultimately boils down to checking its consistency with respect to lower-level theories (much like mathematics), and it is often possible (though not always rational) to resolve empirical difficulties without giving up the theory under examination. It appears therefore that while mathematics is to a certain degree 'science-like', modern science is also much more 'mathematics-like' than has traditionally been supposed, and any difference between the two is at most only a matter of degree.

Although once couched in formal language physical theories are no more directly refutable than mathematical theories, nobody would for that reason deny them their empirical character. Neither should the impossibility of a direct empirical refutation of a mathematical theory count as sufficient reason for denying mathematics all claims to empirical significance. Formalised mathematics can effectively be immunised to all informal counterevidence: a formal mathematical theorem may be upheld 'come what may'. But the same applies to a considerable extent also to modern, mathematically impregnated science. And in either case, our actually choosing to do so would imply resigning ourselves to stagnation of the growth of knowledge. Informal counterexamples to formal theorems can be ignored; but by ignoring them, we also ignore the best opportunities for achieving progress. This is precisely the important lesson contained in Imre Lakatos' work on *Proofs and Refutations* (Lakatos 1963–64, 1976), which may be regarded as the seminal text for the quasi-empirical approach to mathematics.

In the acknowledgement preceding the said articles, Lakatos tells us that 'the paper should be seen against the background of Pólya's revival of mathematical heuristic, and of Popper's critical philosophy' (Lakatos 1976, p. xii). It will be opportune, therefore, to sketch these backgrounds first and next to proceed with an analysis of Lakatos' quasi-empirical heuristic against these backgrounds. Although there are other approaches to the philosophy of mathematics that go under the head of quasi-empiricism, the present discussion will be restricted to the said criticist-objectivist strand, construed as a self-contained whole. A short assessment of the educational implications of the quasi-empirical view of mathematics will be given in the concluding section. These implications have no direct bearing on the actual practice of teaching mathematics in the classroom, but mainly – not less importantly – on the *image* of mathematics that is conveyed in education.

23.2 Pólya's Problem-Solving Heuristic

Lakatos' fellow Hungarian and friend György Pólya (1887–1985) was an important reformer of mathematics education and a champion of informal styles of reasoning in mathematical problem solving (Pólya 1954, 1957, 1962, 1968, 1973). He extensively discussed several ways of fruitful thinking in mathematical problem situations. By its enormous wealth of examples, this extensive body of work had a profound impact on mathematics education.

Underlying Pólya's approach was the crucial distinction between demonstrative and plausible reasoning. Presented in the standard Euclidean manner, mathematics appears as a systematic deductive enterprise. Demonstrative reasoning refers to this well-known deductive or Euclidean mode of presentation. It has rigid standards which are codified and clarified by logic. This style of reasoning is safe, beyond controversy, and final. It is the mode of argumentation needed for the ultimate proof of mathematical propositions.

Plausible reasoning, by contrast, refers to argumentation in the inductive or even experimental style. Mathematics in the making is said to exhibit the character of an experimental inductive science based on plausible rather than demonstrative reasoning. Especially inductive generalisation and reasoning by similarity and analogy are essential for the discovery or invention of conjectures. As problem-solving strategies, they are domain specific and situational; their standards are fluid, not rigid; and they are directed towards both the generation and the support (though not the proof) of mathematical hypotheses.

> Mathematics in the making resembles any other human knowledge in the making. You have to guess a mathematical theorem before you prove it; you have to guess the idea of the proof before you carry out the details. You have to combine observations and follow analogies; you have to try and try again. (Pólya 1973, p. vi)

Pólya thus entertains an 'empiricist' position with respect to the generation of mathematical knowledge and even the generation of proof ideas, though not in regard of proof itself. But in the birth phases of a mathematical theory, in particular, there is ample space for inductive reasoning, generalisation, specialisation and analogy, and these informal modes of reasoning are reproducible in the classroom. The didactic relevance is obvious from the wealth of examples which are offered for imitation and practice, enabling learners to grasp the relevant concepts and to re-create as it were the theory in question. Pólya suggests that the traditional deductive view of mathematics seriously obscures the inductive nature of the reasoning that mathematicians use when deriving their conjectures and dreaming up their attempts at deductive proofs:

> The result of the mathematician's creative work is demonstrative reasoning, a proof, but the proof is discovered by plausible reasoning, by guessing. (Pólya 1954, p. 158)

Pólya was exceptional through his interest in heuristic, the till-then largely neglected problem of the reasoning processes underlying discovery. Especially since Reichenbach's canonisation of the distinction between the context of discovery and the context of justification, methodological analysis had more and more become restricted to the explication of concepts and the verification of already articulated theories. Discovery was considered a process devoid of logic and therefore of interest only to psychologists. For Pólya, however, discovery in mathematics follows certain rules that together represent a 'heuristic', an *ars inveniendi* (art of invention). It concerns the discovery of mathematical 'facts', which subsequently still are to be proved in a strictly deductive way. But heuristic, the logic of mathematics in the making, is largely inductive or, in other words, 'quasi'-empirical.

Pólya's achievements clearly are above all of great pedagogical and didactic relevance. As he himself testified, it had never been his intention to write philosophical treatises. Still, his work contains many philosophically important issues which, however, showed to full advantage only in the hands of Imre Lakatos. Testing mathematical conjectures by 'quasi-experiments' represents just one of the more important examples of what Lakatos owed to Pólya.

23.3 Between Pólya and Popper: Lakatos' Heuristics

Imre Lakatos (1922–1974) went on where Pólya had stopped. He transformed the idea of heuristic into a critical methodological concept, the method of proofs and refutations. In some ways, it surpassed Popper's logic of scientific discovery, but it surpassed even more Pólya's idea of heuristic as an 'art of invention', and especially the latter's inductivist conception. Lakatos' heuristic was based on the use of counterexamples – suggesting falsification – as critical tools for the achievement of *growth* of knowledge.

Heuristic for Lakatos was a truly methodological notion, *viz*., a set of criteria indicating which paths should be followed and which should be avoided in order that our knowledge may grow. It is neither a logical nor a psychological subject, but an autonomous methodological discipline, the 'logic of discovery':

> there is no *infallibilist* logic of scientific discovery, one which would infallibly lead to results; there is a fallibilist logic of discovery, which is the logic of scientific progress. Popper, who has laid down the basis of *this* logic of discovery, was not interested in the metaquestion of what was the nature of his inquiry and he did not realise that this is neither psychology nor logic; it is an independent discipline, 'heuristic'. (Lakatos 1976, pp. 143–144, footnote)

Lakatos not only applied Popper's 'logic of discovery' to mathematics but brought a much larger part of the Popperian corpus to bear on mathematics, *viz*., the centrality of problems and their dynamics rather than static definitions, methodological rules to prevent loss of content, the use of models to test lemmas separately and the associated distinction between global and local counterexamples (cf. Glas 2001), and more especially a group of ideas clustering around Popper's doctrine of the relative autonomy of objective knowledge, which was fully endorsed by Lakatos:

> Mathematical activity is human activity. Certain aspects of this activity … can be studied by psychology, others by history. Heuristic is not primarily interested in these aspects. But mathematical activity produces mathematics. Mathematics, this product of human activity, 'alienates itself' from the human activity which has been producing it. It becomes a living, growing organism that *acquires a certain autonomy* from the activity which has produced it; it develops its own autonomous laws of growth, its own dialectic. (Lakatos 1976, p. 146)

Proofs and Refutations is written in the form of a classroom dialogue between a teacher and pupils bearing the names of Greek letters and representing various ways of dealing with counterexamples. In the beginning, we have a theorem (about the relation between the numbers of vertices, edges and faces of polyhedra) and a counterexample. What follows is a direct confrontation between two equally dogmatic epistemological positions. Pupil Delta typically tries to save the proposition by 'conventionalist stratagems' – introducing ad hoc redefinitions of terms in order to render counterexamples harmless (appropriately dubbed monster barring, exception barring and monster adjustment by Lakatos). These strategies effectively immunise the theorem from refutation but also rid it of more and more of its informative content, until at last it has become an utterly uninteresting truism. Pupil Gamma, on the other hand, insists on exact definitions of the fixed meanings of terms. He therefore regards any counterexample as conclusive proof of the falsity of the theorem. He typically is a 'naïve falsificationist'. Neither Delta nor Gamma handles a critical methodology in the Popperian sense, that is, a set of rules delimiting the sorts of arguments that are fruitful to the *growth* of knowledge, getting at theorems that say 'more' that is also 'more nearly true'. Neither of the dogmatic positions represented by Delta and Gamma *uses* the counterexample in a constructive fashion to learn from it how a better theorem might be obtained. Both Gamma's and Delta's modes of argumentation are in this sense detrimental to the growth of knowledge; they are not rational because they fail to take adequate account of the problem situation.

Rejecting the use of conventionalist stratagems does not imply that all counterexamples should be uncritically accepted; we may rationally defend a theory, provided that adjustments are not entirely ad hoc and do not lead to unnecessary losses of content. So there is always a methodological *decision* to be made when a theorem is confronted with a counterexample, the rationality of which depends on the particular problem situation, especially on whether it would lead to a content-increasing or a content-reducing problem shift.

The teacher develops the Lakatosian methodology by participating in and drawing the lesson from the discussion that follows after the initial confrontation. He lets the pupils lay down the conclusions in a number of methodological rules which, typically, are all concerned with making a justifiable *decision* about what to do if a counterexample, either global (against the theorem as a whole) or local (against a lemma in the proof), turns up. All the rules begin with 'if you have…'; they are not concerned with the question of 'how to find' (Pólya's *ars inveniendi*) but with the logic of discovery in the (Popperian) sense of making justified decisions – justified by preventing loss of content. The rules say that if you have a global counterexample, analyse your proof, make all hidden lemmas explicit, find the guilty one and improve your conjecture by incorporating this lemma in the form of a condition. If you have a local counterexample, check to see whether it is not also global. If it is, apply the previous rule. If it is not, try to improve your proof analysis by replacing the refuted lemma with an unfalsified one (Lakatos 1976, p. 50).

Much of the methodological discussion thus consists in specifying the appropriate methodological rules to counter conventionalist stratagems by turning global counterexamples into local ones and *using* them to get at improved theorems-*cum*-proofs, without unnecessary losses of informative content. But besides preventing loss of content, we aim at increase of content; the fifth methodological rule indicates how this is to be done: if you have counterexamples of any type, try to find, by deductive guessing, a deeper theorem to which they are counterexamples no longer (*ibid*., p. 76). Increase of content may also be achieved through the formation of new concepts as a by-product of the development of the initial naïve conjectures into more and more sophisticated propositions. The formulation, analysis and reformulation of proofs will often, perhaps unconsciously, lead to a redefinition of the terms used – a development from naïve concepts to 'proof-generated' concepts. We may even 'stretch' concepts deliberately beyond their original domain of application in order to reveal possibly unsuspected new relationships that could not even be articulated in terms of the original, more naïve concepts.

Central to the method of *Proofs and Refutations* is the role of *proofs* in the growth of mathematical knowledge. Proofs are not ends, in the sense of establishing once and for all the truth of a theorem, but means to get at richer, deeper, more interesting theorems. Lakatos introduced a structural epistemological similarity between 'proofs' in mathematics and experimental 'tests' in science (proofs are 'tests' – as in the 'proof' of the pudding). As scientific theories are tested by experiments that anchor them to lower-level statements, so mathematical theorems are tentatively proved by deriving them – by means of a thought experiment – from more basic lemmas. Proofs thus play a role analogous to corroborating experimental tests in science. In the justificationist tradition, proofs are supposed to link theorems to indubitable axioms whose truth immerses the whole propositional system through channels of truth preserving – i.e. deductive – arguments. In Lakatos' quasi-empirical heuristic, it is not truth streaming downward from the axioms but the upward retransmission of falsity (in the form of counterexamples) that is crucial for the growth of knowledge.

23.4 Fallibilism and Quasi-Empiricism

The most important background to Lakatos' quasi-empiricism is, of course, the critical fallibilism of his one-time teacher at the London School of Economics, Karl Popper (1902–1994). Popper did not consider anything, including mathematics and even logic, as absolutely certain (Popper 1984, pp. 70–72). He argued that we should never save a threatened theoretical system by ad hoc adjustments that reduce its testability (Popper 1972, pp. 82–83) – a view to be exploited by Lakatos to such dramatic effect in the dialogues of *Proofs and Refutations* under the heads of monster barring, exception barring and monster adjustment.

Popper's fallibilism implies the non-existence of solid foundations to stop the infinite regress in proofs and definitions; all knowledge is conjectural, consisting of attempts at solving problems. Central to mathematics are problems, and striving after exactness for its own sake is futile:

> Absolute exactness does not exist, not even in logic and mathematics . . . and the demand for "something more exact" cannot in itself constitute a genuine problem (except, of course, when improved exactness may improve the testability of some theory). (Popper 1983, p. 277)

In much the same vein, Lakatos took up a critical analysis of modern attempts to place the whole of mathematics on a perfectly exact basis of ultimate logical intuitions in his paper on 'Infinite Regress and Foundations of Mathematics', which dates back to 1962, before the articles on *Proofs and Refutations* appeared (1963–1964) (Lakatos 1978b, pp. 1–23). From the outset, Lakatos made it clear that his aim was to break ground for a critical programme in mathematics, the programme of Popper's *critical fallibilism* (*ibid*., pp. 9–10).

So far, Popper and also Lakatos himself (in his thesis) had only considered *informal* 'preformal' mathematical theories. But it is one thing to show that informal mathematics is conjectural, it is quite another thing to show that uncertainty is not just a *Kinderkrankheit* of informal mathematics, which has now been cured by founding the discipline on rigorous logic and 'ultimate' (set-theoretic) axioms. Mathematical theories are fallible not only as long as they have not been properly founded: the foundational programmes are themselves just hypotheses. The arithmetisation of mathematics by Cauchy and his followers was a wonderful Euclidean achievement, but like any other theory, it was susceptible to criticism. The most incisive critical arguments came from the doubts of the pursuers of the quest for certainty themselves (notably Frege and Russell):

> Have we *really* reached the primitive terms? Have we *really* reached the axioms? Are our truth-channels *really* safe? (*ibid*., pp.10–11)

Lakatos concentrated specially on Russell,

> showing how he failed in his original Euclidean programme, how he finally fell back on inductivism, how he chose confusion rather than facing the fact that what is interesting in mathematics is conjectural. (*ibid*., p. 11)

Russell never had seriously considered the possibility that mathematics may be conjectural. Instead, he came to hold that some axioms of logic are to be believed, not on their own account, but on account of the indubitability of their logical consequences (*ibid*., p. 17). According to Lakatos, Russell failed to draw the right conclusion

> that the infinite regress in proofs and definitions in mathematics cannot be stopped by a Euclidean logic. Logic may *explain* mathematics but cannot *prove* it. It leads to sophisticated speculation which is anything but trivially true. … The logical theory of mathematics is an

> exciting, sophisticated speculation like any scientific theory. It is an empiricist theory and thus, if not shown to be false, will remain conjectural forever. (*ibid*., p. 19)

Lakatos did not deny, of course, that virtually the whole of mathematics could be derived from axiomatic set theory. The fundamental assumptions of set theory, however, are far from self-evident or trivially true. They might be overthrown, replaced or supplemented by new axioms, especially in view of the 'independent' questions, the remaining problems which are not decidable by the standard axioms. Given that these axioms cannot themselves be proved, any sort of arguments that may be offered for or against them will in the end rest on what one *guesses* to be true (or convenient).

Lakatos drew attention to the danger that those (like Russell) who recognise the science-likeness of mathematics turn for similarities to a noncritical (non-Popperian), justificationist image of science, fall back on inductivism and psychologism and keep searching for the ultimate authoritative basis for justifying certain *beliefs*.

> But why on earth have "ultimate" tests, or "final" authorities? Why foundations, if they are admittedly subjective? Why not honestly admit mathematical fallibility, and try to defend the dignity of *fallible* knowledge from cynical scepticism . . . ? (*ibid*., p. 23)

At the London Colloquium of 1965, Lakatos commented on a lecture of Kalmár in which the latter discussed and defended the position that mathematics is an empirical science (Lakatos 1967, pp. 187–194). It is here that Lakatos introduced his distinction between *quasi*-Euclidean and *quasi*-empirical theories and laid down the claim that mathematics is quasi-empirical.

He explained that a theory may be non-empirical yet quasi-empirical, or empirical yet quasi-Euclidean for that matter, the distinction referring only to the direction of the characteristic truth-value flow (top-down or bottom-up). The claim that mathematical theories are quasi-empirical therefore says in effect that the characteristic logical flow in mathematical theories is the bottom-up retransmission of falsity. Euclidean theories are here considered as limiting cases of quasi-empirical theories: a system is Euclidean if it is the logical closure of the accepted basic statements and quasi-empirical if it is not. Whereas a Euclidean theory may be claimed to be true, a quasi-empirical theory can at best be well corroborated (when it has an impressive record of passed tests), but ultimately has to remain conjectural. In a quasi-empirical theory, the axioms do not *prove* the theorems in a strict sense, but they *explain* them by showing of which more fundamental assumptions they are the logical consequences. The basic rule of quasi-empirical methodology is

> to search for bold, imaginative hypotheses with high explanatory and heuristic power; indeed, it advocates an uninhibitedly speculative proliferation of alternative hypotheses to be pruned by severe criticism. (*ibid*., p. 202)

Lakatos deemed it not superfluous to state expressly in a footnote that *of course* the paradigm of quasi-empirical methodology is Popper's scientific methodology.

The axioms of a formal theory are often regarded as implicitly defining the concepts that they introduce. If this view is accepted, then there could be no potential mathematical falsifiers except logical ones (i.e. statements of inconsistency). But

Lakatos vehemently opposed the utterly *un*historical identification of mathematics with the set of all consistent formal systems and insisted that we should speak of formal systems only if they are formalisations of some informal theory. A formal theory then may be said to be ‘refuted’ if one of its theorems is negated by one of the theorems of the corresponding informal theory. Such informal theorems he called *heuristic falsifiers* of the formal theory (Lakatos 1978b, p. 36).

The axioms of set theory, for example, may be tested for consistency, and the definitions may be tested for the correctness of their translation of branches of mathematics such as arithmetic. If a counterexample from arithmetic can be formalised in the system, the formal theory is thereby shown to be inconsistent (in which case we have a logical falsifier). But if the system is consistent, the counterexample cannot be formalised. Such a heuristic falsifier therefore does not show that a formal theory is inconsistent, but only that it is a false theory *of arithmetic*, while it still may be a true theory of some mathematical structure that is not isomorphic with arithmetic. The axioms then do not properly *explain* the informal theory that they were designed to explain.

So Lakatos found mathematical analogues of Popperian potential falsifiers in theorems of arithmetic or other branches of classical mathematics that are potential counterexamples to corresponding theorems of the formalised theory. It enabled him to give an epistemological underpinning to such notions as the content of a mathematical theory (the arithmetical content of a formal theory in particular), content-increasing and content-decreasing problem shifts and so on, in terms of sets of potential falsifiers – as Popper had done for natural science.

Strictly speaking, a heuristic falsifier is no more than a rival hypothesis that merely *suggests* a falsification, and suggestions may be ignored. This, however, does not separate mathematics as sharply from natural science as one might think. Popperian basic statements, too, are only hypotheses after all. They are accepted tentatively for the purpose of a particular discussion of a particular problem, but may become highly questionable in a different discussion of a different problem. They do not constitute some bedrock of knowledge, but are more like ‘piles driven into a swamp’ (Popper 1972, p. 111). Lakatos was fully in agreement with this view when he claimed that

> the crucial role of heuristic refutations is to shift problems to more important ones, to stimulate the development of theoretical frameworks with more content. (Lakatos 1978b, p. 40)

What remains is the question about the basis on which truth values are first injected into the potential falsifiers of mathematical theories. Since on his view the only interesting and respectable formal theories are formalisations of established informal theories, this question in part reduces to inquiring into the nature of the basis on which initial truth values are injected into the basic statements of the informal predecessors. The answer should be sought by tracing back (through rational reconstruction) the series of *problem shifts* that constitutes the development of the field. Perhaps mathematics might ultimately turn out to be ‘indirectly empirical’; or perhaps the source of the initial truth value injection is to be found in construction, or intuition, or convention.

> The answer will scarcely be a monolithic one. Careful historico-critical case-studies will probably lead to a sophisticated and composite solution. But whatever the solution may be, the naïve school concepts of static rationality like *a priori*/*a posteriori*, *analytic*/*synthetic* will only hinder its emergence. These notions were devised by classical epistemology to classify Euclidean certain knowledge – for the problem shifts in the growth of quasi-empirical knowledge they offer no guidance. (*ibid*., pp. 40–41)

23.5 Mathematical Quasi-Experiments

The pivot on which Lakatos' programme turned was his construal of informal proofs as thought experiments for the appraisal of mathematical knowledge. The standards of appraisal do not come from the study of foundations and formal systems, but from the logic of proofs and refutations, that is, of quasi-experimental tests and improvements. Mathematics is like science, not because it is somehow based on sensual experiences, but because it likewise proceeds through fallible trials and tests, and for this reason, it may be called a quasi-experimental science.

The science-like practice of working 'upwards' from facts to theories (lemmas, axioms, rules) corresponds nicely with the age-old 'method of analysis and synthesis', which pervades the entire history of exact science and of which Lakatos' method of proofs and refutations may be considered a logical extension. In analysis, a mathematical conjecture is tested by searching for concomitants that must be true if the conjecture were true. If in so doing one hits upon an obvious falsity, the conjecture must be false. But if only already established or trivial truths are hit upon, the conjecture may be true. Synthesis then consists of the construction of a compelling argument with the aid of the insights learned from the analysis. Lakatos' method goes on to test in this way the proofs themselves, searching for heuristic counterexamples in order to make hidden lemmas explicit and thus to get at improved theorems-*cum*-proofs, with enhanced generality, scope, profundity, problem-solving and explanatory power, etc.

On Lakatos' view, the Greeks had subjected the unproven mathematical facts inherited from the barbarians to a great many such analyses. They found that some lemmas kept cropping up, whereas their alternatives remained sterile, thus yielding series of corroborated analytical components converging on a small number of indubitable truths, which were to constitute the hard core of axiomatisation programmes such as Euclid's *Elements*.

This account can in fact be substantiated by Euclid's proposition 32, which says that any exterior angle of a triangle equals the sum of the opposite interior angles and that the sum of the interior angles equals two right angles. For the proof, one has to produce the side AC of a triangle ABC beyond C and to draw a line through C parallel to AB. The proposition then can be 'seen' to follow directly from the equality of the angles that the said parallel makes with the sides AC and BC. Thus the statement about parallels is the premise from which the synthetic argument starts, and by reversing it, one gets a glimpse of the analytic procedure through which the premise was originally found. By producing lines and drawing parallels, many properties of figures could be seen to be consequences of the said property of parallels, which thus became a hard-core element in the axiomatisation.

Curiously enough, Euclid's fifth postulate, the so-called parallel postulate, does not speak of parallels, although the relevant properties of parallels are direct consequences of it. It says that two lines will meet, if sufficiently produced, at the side on which the sum of the interior angles with an intersecting line is less than two right angles. This formulation is highly suggestive indeed of the above account of its analytic origins. The equality of angles in the proof of proposition 32 follows immediately in case the sum of the said interior angles happens to be exactly equal to two right angles.

The analytic-synthetic procedure is an 'experiment' in that it involves 'real' actions (drawing and producing lines) in order to 'see' how certain properties of figures obtain. This way of 'seeing' is not based on logical connections between statements, but on intuitively recognisable relations between and within figures, which as such are not readily formalisable. What is laid down in the postulates are not truths but requirements for the construction of geometric demonstrations; it is required, for instance, 'that through any two points a line can be drawn' (post.1), 'that any line can be produced' (post.2), 'that given a (mid) point and a line (radius) the circle can be drawn (post.3) and 'that all right angles are equal' (post.4). The procedure is *quasi*-experimental in that the actions are idealised: although visible lines and points occupy space, a *mathematical* point is defined as 'that which occupies no place' and a *mathematical* line as 'length without breadth'. These definitions make sense only if one assumes every rational person to be already in possession of intuitive notions of what a point (dot) and a line (stripe) are; they merely stipulate which aspects of these intuitions may, and which may not, be used in a mathematical demonstration. The experiment is done by drawing visible lines through visible points, but in the argumentation, abstraction is made of their sensual features.

Analysis became especially important as a method for proving *ex absurdo*, in which case the negation of a proposition is analysed. For when a concomitant of the negated proposition is found to be obviously false, this proves indirectly that the proposition itself must be true. The analysis as such proves the proposition, and the (often laborious) task of constructing a synthetic argument can be avoided. Greek mathematics after Euclid thus came to abound with indirectly proven propositions, without the slightest hint as to the way in which they were discovered, and also without the intuitively compelling demonstrations that synthetic proofs supply. The heuristic dimension being almost completely hidden from view, the classical image of mathematics as a deductively closed Euclidean system became firmly established for a long time to come. If Archimedes' treatise *On Method* (to be discussed in what follows) had not been discovered (in 1906), virtually nothing at all would have been known about Greek heuristics (Lakatos 1978b, p. 100).

In contrast to Lakatos' negative view of premature axiomatisation, Hintikka and Remes have shown convincingly that even in an axiomatised system, the construction of a proof required a veritable method of discovery, and analysis furnished this method. It involved the introduction of tentative auxiliary constructions, which necessitated a subsequent synthesis to warrant the results. What was analysed were configurations, not deductive connections or proofs, and the steps of analysis did not lead from one proposition to another, but from figure to figure (Hintikka and Remes 1974, p. 32). The need of introducing auxiliary constructions constituted the unpredictable and recalcitrant element in the methodological situation. The natural course of an analysis was not linear but took the form of a more complicated network of connections, and this made synthesis non-trivial and necessary for warranting the reversibility of the several steps. This presented no insuperable difficulties, as in a geometrical analysis the steps will be reversible anyhow, being mediated by functional interdependencies between geometrical entities in a given figure (*ibid.*, p. 37). The aim of the analysis was to find the *crucial* auxiliary constructions, but this aim could only be attained if enough hypothetical constructions were already anticipated in the analysis. One had to trust one's intuitive insight in finding the relevant geometrical interdependencies, and this way of proceeding made it imperative to justify the procedure afterwards by a synthesis: together they constituted two inseparable halves of one quasi-experimental method.

The creators of modern science – Descartes, Galileo and Newton – held the ancient method of analysis and synthesis in high esteem and shaped their methodology on it (for a general overview, see Otte and Panza 1996). I will present just a few examples to illustrate my earlier statement that not only is mathematics science-like, science is also mathematics-like, which indeed renders the classical *a priori/a posteriori* and *analytic/synthetic* distinctions merely a matter of degree.

Geometrical analysis was a systematic inquiry into the interdependencies between known and unknown 'objects' in a given configuration, and it was but a relatively small step to regard a real experimental setup likewise as a sort of analytic situation. Galileo's seemingly 'real' experiments, for instance, turn out to have been intended as demonstrations that the effects calculated on the basis of presumed relationships could actually be produced. These relationships as such had however been discovered in a 'quasi-mathematical' way, through thought experiments.

The insight, for instance, that in vacuum all objects fall with the same speed, was obtained in the following way. Suppose a heavy object H falls faster than a lighter object L – as common opinion would have it. Now connect both objects through a thread of negligible weight. As object H now has to pull the slower object L, it will move less fast than when falling alone. On the other hand, the combined object is heavier and therefore would have to fall faster. From this contradiction, it follows that the supposition must have been false. So all objects fall with the same speed.

Galileo's version of inertial movement was based on consideration of the movement of objects on an inclined plane. Movement upwards on this plane will be decelerated, and movement downwards will be accelerated, so movement on a horizontal plane (abstraction made of resistance) will continue uniformly. Note that 'horizontal' here means parallel to the surface of the earth. Galileo's inertial motion is circular.

As he wrote in a letter:

> I argue *ex suppositione* about motion, so that even though the conclusions should not correspond to the events of the natural motion of falling heavy bodies, it would little matter to me, just as it derogates nothing from the demonstrations of Archimedes that no moveable is found in nature that moves along spiral lines. But in this I have been, as I shall say, lucky; for the motion of heavy bodies and its events correspond punctually to the events demonstrated by me from the motion I defined. (letter of 1639, quoted in Drake 1975, p. 156)

In fact Galileo had begun by defining uniformly accelerated motion as 'such motion of which the increment of speed is proportional to the distance traversed' and replaced 'distance traversed' by 'time passed' only after he had noticed that the calculations based on the former definition did *not* conform to the properties of natural accelerated motions such as free fall.

Both Galileo's method and the new science of motion to which it gave rise were indeed moulded on the typical example set by Archimedes in his treatise *On Method*. It concerns the determination of the area of the segment of a parabola by means of an analogy with statics – applying what is now known as Archimedes' law of the lever. His reasoning did not consist of a linear chain of deductive arguments, but involved a complicated network of known relations within and between figures. He 'thought of' line segments parallel to the axis of the parabola and contained within the segment of the parabola as weights and, by invoking the said network of relations, was able to 'balance' them against corresponding line segments within an inscribed triangle (T) with the same base and height as the segment. As 'all' the line segments making up the figures could thus be set in equilibrium, the segment as a whole could be balanced against the total weight (=area) of the said triangle, placed in its centre of gravity. The law of the balance then gave the ratio between the area of the segment of the parabola and that of its inscribed triangle as 4:3 (Dijksterhuis 1987, Chap. X) (for a more detailed account of this and still other examples of mathematical thought experiments, see Glas 1999).

Archimedes regarded his method as a way of exploring, not of proving. However, the reason for this was not that it involved mechanical notions, but only that taking areas to be made up of line segments lacked demonstrative force. In his treatise *Quadrature of the Parabola* (Dijksterhuis op.cit., Chap. XI), he once more demonstrated the same theorem by means of statical considerations, but this time without 'summing' line segments, and here the argument was presented as a geometric proof that satisfied all requirements of exactitude.

Still, the thought experiment was of vital importance not only for the discovery of the mathematical proposition but for its final justification (proof) as well – which makes it a nice example of Lakatos' interpretation of proofs as quasi-experiments. The ratio found by means of the balancing experiment entered in the very reasoning through which the crucial lemma for the final proof was constructed. The procedure can be reconstructed as follows:

The inscribed triangle (T) cuts off two new segments, in which triangles with the same base and height as these segments can be inscribed. Together their areas can be shown to be (1/4)T. The same procedure can be applied to the new segments thus obtained and so forth. After n steps, the total area covered by the triangles will be

$(1+1/4+1/16+\ldots+1/4^n)$T. Now assuming the outcome of the thought experiment to be true, the segments generated in each step will exceed their inscribed triangles by 1/3, so that adding $(1/3)(1/4^n)$ to the last term of the series should yield the hypothesised value (4/3)T. And indeed the last two terms of the series $1+1/4+\ldots+1/4^n+(1/3)(1/4^n)$ add up to $(4/3)(1/4^n)=(1/3)(1/4^{n-1})$, and this added to the previous term in the series yields $(1/3)(1/4^{n-2})$, etc. The series 'eats' itself as it were from tail to head. Therefore, the sum of the whole series equals $1+1/3=4/3$. Accordingly, the area covered by the inscribed triangles after n steps equals $4/3-(1/3)(1/4^n)$ times T (we have to subtract the $(1/3)(1/4^n)$ that was first added to the series). To this lemma, found by using the outcome of the thought experiment as guiding hypothesis, the double argument 'ex absurdo' could be applied which finally delivered the exact proof.

This kind of proof required the adoption of a lemma of Euclid's: 'if from a quantity is subtracted more than half, from the remainder again more than half, and so on, it will at length become smaller than any pre-assigned quantity'. The proof then consisted in showing that the area of the segment cannot possibly be smaller than (4/3)T, for however small one assumes the difference to be, the term $(1/3)(1/4^n)$ can in virtue of the said lemma always be made smaller still by taking n great enough. The assumption that the area of the segment would be greater than (4/3)T is refuted in a similar fashion. Therefore the area of the segment cannot possibly be either greater or smaller than (4/3)T; hence it necessarily must be exactly (4/3)T.

As already said, it was the thought experiment itself that delivered the necessary tools for the construction of a rigorous proof. It was not just a suggestive aid in discovery but also delivered essential structuring and guiding assumptions for the construction of the crucial lemma for the final proof. Heuristic and justificatory procedures are complementary, the former necessitating the latter and the latter depending on the former for their crucial structuring and guiding assumptions.

Mathematics does proceed through 'trying out and testing' but also in a somewhat wider, less theory-centred sense than envisioned by Lakatos. Not all scientific experiments are tests of theories, and the same is true of thought experiments. Not all trials and tests in mathematics are aimed at proving and refuting propositions – as Lakatos would have it – nor are discovery and innovation confined to the preformal or pre-axiomatic phases of a mathematical theory (this point is also argued by Corfield 1997, 1998). Thought experimentation also is a major analytic tool for conceptual development and change by bringing to light unsuspected connections between different scenes of inquiry, which enable progress to more comprehensive, integrated and unified theories.

Although the prefix 'thought' might suggest otherwise, thought experiments need not literally be performed in thought in the sense of involving mental representations or images. Archimedes 'thought of' line segments as possessing weight, but this is not essentially different from normal geometric practice, in which lines, for instance, are 'thought of' as possessing length but not breadth, etc. The way in which Archimedes conducted his statical argument was in all respects similar to the construction of a geometric proof. Archimedes also based his statics proper on postulates – not empirical generalisations – in exactly the way in which Euclid had axiomatised plane geometry and in which Galileo much later founded his new science of motion.

In mathematics and science alike, (thought)experiments are attempts *at once* to prove a theory *and* to *im*prove it. Proofs in informal mathematics do not justify accepting a result unconditionally, but they do justify accepting it provisionally, until it is improved by a new thought experiment. The improvement is a 'refutation' of the previous result only in the sense that it shows it to be lacking in generality and scope, deficient in unifying, explanatory and problem-solving capacity as compared with the new result, which not only implies a better proof but a better theorem as well.

23.6 Popper's Quasi-Empiricist View of Mathematics

Popper had not originally intended his methodology of conjectures and refutations to apply to mathematics, but he was delighted with Lakatos' having it thus applied (see, for instance, Popper 1981, pp. 136–137, 143, 165). One typical statement that shows Popper's endorsement of Lakatos' quasi-empiricist philosophy of mathematics is the following:

> The main point here I owe to Lakatos' philosophy of mathematics. It is that mathematics (and not only the natural sciences) grows through the criticism of guesses, and bold informal proofs. (*ibid.* p.136)

Lakatos not only applied Popper's method in a domain which Popper had not envisaged but also brought a much larger part of the Popperian corpus to bear on mathematics, especially the doctrine of the relative autonomy of objective knowledge, which is part and parcel of the 'dialectic' of *Proofs and Refutations* and hence of quasi-empiricism. It is this objectivism, of course, that made him in the said work to focus on the rationally reconstructed history of problems, theoretical proposals, critical arguments and so on and to relegate the 'real' history of the thoughts and ideas of 'real' mathematicians to the footnotes.

It is in his discussion of Brouwer's intuitionism (Popper 1981, p. 134f) that we get a clear idea of the implications of Popper's objectivist philosophy for mathematics. Brouwer had been right in insisting that mathematics is a human creation or invention, but failed to see that it is also partially autonomous. Popper's 'epistemology without a knowing subject' is an account of how mathematics can be man-made *and* relatively autonomous at the same time, that is, how mathematical objects can be said in a way to exist objectively *although* they are human creations (for a more detailed account of Popper's philosophy of mathematics, see Glas 2001 and 2006).

Brouwer's 'primal intuition of time' cannot be an authoritative source of knowledge, simply because there are no authoritative sources of knowledge. Any proposed rock-bottom principle, whether self-evidence, indubitability, primal intuition or whatever – introduced to stop the infinite regress of proofs – would make critical discussion impossible when there is no agreement on such a principle. But different people at different times happen to have quite different intuitions about what is self-evident and what is indubitable. On Popper's view, intuition is a culture- and time-dependent phenomenon which *changes* with the development of science and the use of argumentative language:

> discursive thought (i.e., sequences of linguistic arguments) has the strongest influence upon our awareness of time, and upon the development of our intuition of sequential order. (*ibid*., p. 138)

The objectivity of mathematics is inseparably linked with its criticisability, and therefore with its linguistic expression:

> Language becomes the indispensable medium of critical discussion. The objectivity, even of intuitionist mathematics, rests, as does that of all science, upon the criticizability of its arguments. (*ibid*., pp. 136–7)

> Though originally constructed by us, the mathematical objects (the objective contents of mathematical thought) carry with them their own unintended and sometimes undreamt-of consequences. For instance, the series of natural numbers – which is *constructed* by us – creates prime numbers – which we *discover* – and these in turn create problems which are certainly not our own invention. *This is how mathematical discovery becomes possible*. Moreover, the most important mathematical objects we discover . . . are *problems* and new kinds of *critical arguments.* (*ibid*., p. 138)

It is in this sense that mathematical objects and problems may be said to have an independent and 'timeless' existence (i.e. irrespective of when, if ever, people become aware of them). Like Plato, Hegel and others, Popper used mathematics as the paradigmatic example of the relative autonomy of the world of intelligibilia (all that which can be an object of thought), which he called the 'third world'. It is not a static but a developing realm which

> has grown far beyond the grasp not only of any man, but even of all men (as shown by the existence of insoluble problems). (Popper 1981, p. 161)

But of course Popper was neither a Platonist nor a Hegelian. In sharp contrast to Hegel and Plato, he tried to bring the (third) world of objective ideas down to earth and to analyse its relationships with the physical (first) and the mental (second) world. Plato's world of ideas was inhabited by perfect and unchanging concepts in themselves; Popper's third world is man-made, imperfect and ever changing, consisting not of immutable concepts but of fallible theories, problems and arguments. Hegel's 'objective mind' was changing, too, but entirely of its own accord, following the dialectic of thesis, antithesis and synthesis, in which physical, mental and logical processes were considered 'identical'. Popper's third world, to the contrary, is the evolutionary product of the rational efforts of humans, who by trying to *eliminate* contradictions in the extant body of knowledge produce new theories, arguments and problems. Far from being 'identical' with the mental world, let alone the physical world, the third world *interacts* with them, but only through one or more subject's being aware (perhaps erroneously) of third-world relationships.

Popper's book *Objective Knowledge* dates from 1972, but essential parts of it had already been published in 1968, whereas the underlying *objectivist* epistemology had of course been paramount in Popper's works from the very beginning (e.g. Popper 1972, pp. 31–32, 44–48). The contents of theories or statements stand in logical relationships with each other – we might, for example, ask whether a statement is compatible with a theory, whether propositions are consistent with each other or contradictory, whether one is the deductive consequence of another or others, whether an inference is valid or invalid and so on. All these are *objective* questions; they are independent of the mental states (belief, conviction, doubt, etc.) that persons can have with respect to the contents involved. Objective contents thus possess various properties and relationships that are independent of anybody's being aware of them, and it is these objective features that are the concern of the objectivist theory of knowledge. It is of course perfectly well possible, and also highly interesting, to study knowledge as a mental phenomenon, in which case we are engaged in empirical scientific (psychological) inquiry (but here also it is advisable to take the objective features of knowledge into account, cf. Popper 1981, p. 149). Philosophical epistemology, on the other hand, is 'epistemology without a knowing subject': it studies objects and relationships in the third world, which consists of the *products* of human mental efforts, products which (by their unforeseeable and incalculable objective entailments) transcend the grasp of their producers and hence come to exist as objective artefacts.

It is of course trivially true that knowledge in the said objective sense can subsist without anybody being aware of it, for instance, in the case of totally forgotten theories that are later recaptured from some written source. It also has significant effects on human consciousness – even observation depends on judgements made against a background of objective knowledge – and through it on the physical world (for instance, in the form of technologies). Human consciousness thus typically acts as a mediator between the abstract and the concrete, or the world of culture and the world of nature. To acknowledge that linguistically expressed knowledge can subsist without humans, that it possesses independent properties and relationships, and that it can produce mental and also – indirectly – physical effects, is tantamount to saying that it in a way exists. Of course, it does not exist in the way in which we say that physical or mental objects or processes exist: its existence is of a 'third' kind.

Popper's insisting upon the crucial distinction between the objective (third-world) and the subjective (second-world) dimension of knowledge enabled him also to overcome the traditional dichotomies between those philosophies of mathematics that hold mathematical objects to be human constructions, intuitions, or inventions, and those that postulate their objective existence. His tripartite epistemology accounts for how mathematics can at once be autonomous *and* man-made, that is, how mathematical objects, relations and problems can be said in a way to exist independently of human consciousness *although* they are products of human (especially linguistic) practices. Mathematics is a human activity, and the product of this activity, mathematical knowledge, is a human creation. Once created, however, this product assumes a partially autonomous and timeless status (it 'alienates' itself from its creators, as Lakatos would have it), that is, it comes to possess its own objective, partly unintended and unexpected properties, irrespective of when, if ever, humans become aware of them.

Popper regarded mathematical objects – the system of natural numbers in particular – as products of human language and human thought: acquiring a language essentially means being able to grasp objective thought *contents*. The development of mathematics shows that with new linguistic means new kinds of facts and in particular new kinds of problems can be described. Unlike what apriorists like Kant and Descartes held, being human constructions does not make mathematical objects completely transparent, *clair et distinct*, to us. For instance, as soon as the natural numbers had been created or invented, the distinctions between odd and even, and between compound and prime numbers, and the associated problem of the Goldbach conjecture came to exist objectively: Is any even number greater than 2 the sum of two primes? Is this problem solvable or unsolvable? And if unsolvable, can its insolvability be proved? (Popper 1984, p. 34). These problems in a sense have existed ever since humankind possesses a number system, although during many centuries nobody had been aware of them. Thus we can make genuine *discoveries* of independent problems and new hard facts about our own creations, and of objective (not merely intersubjective) truths about these matters.

Nothing mystical is involved here. On the contrary, Popper brought the Platonist heaven of ideal mathematical entities down to earth by characterising it as objectivised *human* knowledge. The theory of the third world at once accounts for the working mathematician's strong feeling that she or he is dealing with something real, and it explains how human consciousness can have access to abstract objects. These objects are not causally inert: for instance, by reading texts we become aware of some of their objective contents and the problems, arguments, etc., that are contained in them, so that the Platonist riddle of how we can gain knowledge of objects existing outside space and time does not arise.

Cultural artefacts like mathematics possess their own partially autonomous properties and relationships, which are independent of our awareness of them: they have the character of hard facts that are to be *discovered*. In this respect they are very much like physical objects and relations, which are not unconditionally 'observable' either, but are only apprehended in a language which already incorporates many theories in the very structure of its usages. Like mathematical facts, empirical facts are thoroughly theory-impregnated and speculative, so that a strict separation between what traditionally has been called the analytic and the synthetic elements of scientific theories is illusory. The effectiveness of pure mathematics in natural science is miraculous only to a positivist, who cannot imagine how formulas arrived at entirely independently of empirical data can be adequate for the formulation of theories supposedly inferred from empirical data. But once it is recognised that the basic concepts and operations of arithmetic and geometry have been designed originally for the practical purpose of counting and measuring, it is almost trivial that all mathematics based on them remains applicable exactly to the extent that natural phenomena resemble operations in geometry and arithmetic sufficiently to be conceptualised in (man-made) terms of countable and measurable things and thus to be represented in mathematical language.

It is especially the (dialectic) idea of *interaction* and partial *overlap* between the three worlds that makes Popper's theory to transcend the foundationist programmes. Clearly, objective knowledge – the objective contents of theories – can exist only if those theories have been materially realised in texts (at world-1 level), which cannot be written nor be read without involving human consciousness (at world-2 level).

Put somewhat bluntly, Platonists acknowledge only a third world as the realm to which all mathematical truths pertain, strictly separated from the physical world; intuitionists locate mathematics in a second world of mental constructions and operations, whereas formalists reduce mathematics to rule-governed manipulation with 'signs signifying nothing', that is, mere material (first-world) 'marks'. In all these cases, reality is split up into at most two independent realms (physical and ideal or physical and mental), as if these were the only possible alternatives. Popper's tripartite world view surpasses physicalist or mentalist reductionism as well as physical/mental dualism, emphasising that there are *three* partially autonomous realms, intimately coupled through feedback. The theory of the interaction between all three worlds shows how these seemingly incompatible mathematical ontologies can be reconciled and their mutual oppositions superseded (Popper 1984, pp. 36–37; cf. Niiniluoto 1992).

To stress the objective and partly autonomous dimension of knowledge is not to lose sight of the fact that it is created, discussed, evaluated, tested and modified by human beings, nor does it imply that the role of mathematicians is reduced to passive observation of a pre-given realm of mathematical objects and structures – no more than that the autonomy of the first world would reduce the role of physicists to passive observation of physical states of affairs. On the contrary, the growth of mathematical knowledge is almost entirely due to the constant feedback or 'dialectic' between human creative action upon the third world and the action of the third world upon human thought.

Every theory, whether mathematical or scientific or metaphysical, is rational on Popper's view exactly

> in so far as it tries to solve certain problems. A theory is comprehensible and reasonable only in its relation to a given problem situation, and it can be discussed only by discussing this relation. (Popper 1969, p. 199)

In mathematics as in science, it is always problems and tentative problem solutions that are at stake:

> only if it is an answer to a problem – a difficult, a fertile problem, a problem of some depth – does a truth, or a conjecture about the truth, become relevant to science. This is so in pure mathematics, and it is so in the natural sciences. (*ibid*., p. 230)

Popper clearly did not view mathematics as a formal language game, but as a rational problem solving activity based, like all rational pursuits, on speculation and criticism.

Although they have no falsifiers in the logical sense (they do not forbid any singular spatiotemporal statement), mathematical as well as logical, philosophical, metaphysical and other non-empirical theories can nevertheless be critically assessed for their ability to solve the problems in response to which they were designed, and accordingly improved along the lines of the *situational* logic or *'dialectic'* indicated above. In particular, mathematical and other 'irrefutable' theories often provide a basis or framework for the development of scientific theories that *can* be refuted (Popper 1969, Chap. 8) – a view which later was to inspire Lakatos' notion of scientific research programmes with an 'irrefutable' hard core. Indeed, his *Methodology of Scientific Research Programmes* (Lakatos 1978a) was largely based on insights obtained through applying (in *Proofs and Refutations*) Popper's logic of scientific discovery to mathematics – and not merely in response to Kuhn's strictures, as has too often been claimed (compare Glas 1995).

Most characteristic of Popper's approach to mathematics was his focussing entirely on the dynamics of conceptual change through the dialectic process outlined, replacing the preoccupation of the traditional approach with definitions and explications of meanings. Interesting formalisations are not attempts at clarifying meanings but at solving problems – especially eliminating contradictions – and this has often been achieved by *abandoning* the attempt to clarify, or make exact, or explicate the intended or intuitive meaning of the concepts in question – as illustrated in particular by the development and rigorisation of the calculus (Popper 1983, p. 266). From his objectivist point of view, epistemology becomes the theory of problem solving, that is, of the construction, critical discussion, evaluation, and critical testing, of competing conjectural theories. In this, everything is welcome as a source of inspiration, including intuition, convention and tradition, especially if it suggests new problems. Most creative ideas are based on intuition, and those that are not are the result of criticism of intuitive ideas (Popper 1984, p. 69). There is no sharp distinction between intuitive and discursive thought. With the development of discursive language, our intuitive grasp has become utterly different from what it was before. This has become particularly apparent from the twentieth-century foundation crisis and ensuing discoveries about incompleteness and undecidability. Even our logical intuitions turned out to be liable to correction by discursive mathematical reasoning (*ibid.* p. 70). Nothing is entirely beyond doubt.

23.7 Conclusion

As said at the outset, my discussion of quasi-empiricism has been confined to the criticist-objectivist tradition connected with the names of Lakatos and Popper. Consequently all other approaches to the philosophy of mathematics that go under this or a similar heading have been omitted. One might think in particular of physicalist approaches such as collected in Irvine (1990) and various other studies focussing on science-like aspects of mathematics and of mathematical practice (for a small selection, see 'suggested further reading'). As it would have been impossible within the available space to do these other approaches sufficient justice, I have preferred to restrict myself to the said critical tradition. This choice enabled me also to present my subject as one coherent whole, rather than getting the discussion scattered in a wide diversity of directions.

Although Lakatos' seminal work on *Proofs and Refutations* was written in the form of a fictitious classroom dialogue, it was intended to represent a rational reconstruction of a particular historical development, and most certainly not as a recommendation for the teaching of mathematics in school. By the same token, the present article does not have any direct implications for the actual practice of classroom teaching. Its educational relevance lies in the *image* of mathematics that it conveys, which might inspire teachers in their practice, for instance, by taking a less rigid stance, eschew formalism, invoke practical experiences and insights, make room for exploration, the formation and testing of conjectures, etc. One example of a proposal concerning the teaching of geometry in this manner is given by Chazan (1990).

The idea of three rather than two ‘worlds’ – which moreover partially overlap and interact – is educationally important in several respects. Firstly, it enables us to overcome traditional dualisms such as between realism and constructivism. It is, for instance, perfectly well possible to be at once a constructivist and a realist with respect to the objective content of mathematics. For even if they are invented by ourselves, mathematical constructions are not arbitrary, nor are they entirely transparent even to their creators. We can make genuine discoveries of entirely unsuspected properties and relationships concerning our own creations.

Secondly, it evidently bears directly on our image of mathematics and the way in which it is culturally embedded. In order to acknowledge the social and cultural dimension of mathematics, there is no need to question the objectivity and partial autonomy of mathematical knowledge. It is sufficient to shift our focus, away from the ways in which new truths are derived, towards the ways in which new problems are conceived and approached. There is indeed much more to mathematics than mere accumulation of true statements. Mathematicians are not interested just in truths (let alone truisms), but in truths that provide answers to questions that are worthwhile and promising in the contemporary – socially and culturally contingent – scene of inquiry. In this way the quasi-empiricist trend in modern philosophy of mathematics may contribute significantly to the further humanisation of the discipline.

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Chapter 24
History of Mathematics in Mathematics Teacher Education

Kathleen M. Clark

24.1 Introduction

The use of the history and in related ways philosophy of mathematics in teaching mathematics has been the subject of discussions in everything from the didactics of mathematics in primary and secondary mathematics teaching to its appropriate role in the education of teachers of mathematics at the primary and secondary[1] level. Given the narrower literature base in this field, the ways in which philosophy of mathematics plays a role in the preparation of mathematics teachers will not be addressed in this chapter. It is worth noting, however, that many contributions shed light on how philosophical perspectives can accurately capture and describe the development of mathematical thinking. For example, in a recent description of his research, Radford (2012) claimed that "algebraic thinking cannot be reduced to an activity mediated by notations" (p. 690). Furthermore, Radford has also described ways in which historical-epistemological analyses "provide us with interesting information about the development of mathematical knowledge within a culture and across different cultures," as well as information about "the way in which the meanings arose and changed" (Radford 1997, p. 32).

The chapter is organized into seven sections. First, a brief overview of arguments that advocate for the use of history in mathematics education and the research perspectives that correspond to this advocacy are presented. In Sects. 24.2 and 24.3, descriptions of the role that history of mathematics has played in mathematics teacher education in the United States (Sect. 24.2) and elsewhere (Sect. 24.3) are given. Section 24.4 elaborates on the reasons for using history of mathematics in

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[1] Although various locations around the world may use "primary" and "secondary" differently, in this chapter, "primary" level corresponds to the school years or grade levels for pupils aged 5–11 and "secondary" level corresponds to years or grade levels for pupils aged 12–18.

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teaching mathematics. Next, Sects. 24.5 and 24.6 discuss examples of empirical studies that were conducted with prospective teachers of primary mathematics and secondary mathematics, respectively. Finally, Sect. 24.7 outlines examples of research from the "next generation" of infusing history in mathematics education, that is, the accounts of practicing teachers who incorporated history of mathematics in teaching at the primary, secondary, and tertiary levels.

24.2 Arguing for the History of Mathematics in Mathematics Education

Lockhart (2008) posed the following questions in "A Mathematician's Lament":

> What other subject is routinely taught without any mention of its history, philosophy, thematic development, aesthetic criteria, and current status? What other subject shuns its primary sources – beautiful works of art by some of the most creative minds in history – in favor of third-rate textbook bastardizations? (Lockhart 2008, p. 9)

Although the main idea of his essay was to highlight the critical issues of a broken mathematics education system in the United States, Lockhart made frequent reference to the necessity of history in teaching and learning mathematics. In his criticism of mathematics in general and standardized curricula and assessments in particular, Lockhart complained about "the complete absence of art and invention, history and philosophy, context and perspective from the mathematics curriculum" (p. 13). Moreover, he condemned those who ask students to learn mnemonic devices (e.g., "SohCahToa" in geometry or trigonometry[2]) or "succumb to 'cutesyness'" to remember area and perimeter formulas for circles[3] (p. 9), rather than relating the real story of the development of a concept, such as "the one about [humankind's] struggle with the problem of measuring curves; about Eudoxus and Archimedes and the method of exhaustion; about the transcendence of pi" (p. 9).

Consideration of the value and importance of using history of mathematics in mathematics education has taken place over many decades. In the United Kingdom, encouragement for the inclusion of historical aspects of mathematical topics has appeared in documents for their National Curriculum – off and on – for over 100 years. Fauvel (1991) cited several excerpts from school curriculum documents, which included directives such as:

> …[P]ortraits of the great mathematicians should be hung in the…classrooms, and that reference to their lives and investigations should be frequently made by the teacher in his lessons, some explanation being given of the effect of mathematical

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[2] This mnemonic device, SohCahToa, is employed by school mathematics teachers (and their students) to remember the basic right triangle ratios of **s**ine = **o**pposite (side)/**h**ypotenuse; **c**osine = **a**djacent (side)/hypotenuse; and **t**angent = **o**pposite (side)/**a**djacent (side).

[3] One such mnemonic device in the form of a "cutesy" anecdote is: "Mr. C, who drives around Mrs. A, and tells her how nice his two pies are ($C = 2\pi r$) and how her pies are square ($A = \pi r^2$)" (Lockhart 2008, p. 9).

> discoveries on the progress of civilization. (Report of Mathematical Association Committee 1919)

> The teacher who knows little of the history of Mathematics is apt to teach techniques in isolation, unrelated either to the problems and ideas which generated them or to the further developments which grew out of them. (British Ministry of Education 1958)

> The mathematics teacher has the task…of helping each pupil to develop so far as is possible his appreciation and enjoyment of mathematics itself and his realization of the role which it has played and will continue to play both in the development of science and technology and of our civilization (The Cockcroft Report 1982). (Fauvel 1991, p. 3)

Fauvel also noted, however, that beginning in the early 1990s, "the historical perspective [was] less noticeable… than in any official document about mathematics education for a century" (p. 3). The national mathematics curriculum in England today explicitly requires that the "historical and cultural roots of mathematics [be] part of the entitlement for every child's experience of mathematics" (Barbin et al. 2011, p. 37).

A similar "history" is mirrored in mathematics education documents in the United States. In the opening chapter of the thirty-first yearbook of the National Council of Teachers of Mathematics (1969), *Historical Topics for the Mathematics Classroom,* Phillip S. Jones described the struggle in using history in the mathematics classroom:

> Teaching so that students understand the "whys," teaching for meaning and understanding, teaching so that children see and appreciate the nature, role, and fascination of mathematics, teaching so that students know that men are still creating mathematics and that they too may have the thrill of discovery and invention – these are objectives eternally challenging, ever elusive. (Jones 1969, p. 1)

This elusiveness may be due in part because as the editors of the yearbook themselves admitted, their goal was to "emphasize the mathematical content of the material and to leave the method of bringing it into the individual classroom in the hands of the person most qualified to make this decision – the teacher" (Baumgart et al. 1969, pp. x–xi).

The opportunities for teachers to learn history of mathematics, particularly during their pre-service teacher preparation program, are the primary reasons why variability exists in how mathematics teachers are able to use history of mathematics in teaching. And, if teachers are not afforded the opportunity to study history of mathematics during teacher preparation programs, then upon entering the teaching profession they have a minute chance, if any, to participate in formal study of history of mathematics and why it is beneficial for using in teaching mathematics.[4] This is problematic when considering national standards for mathematics teachers that call for goals aimed at providing experiences for pupils that included historical and cultural perspectives.

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[4] This observation is made with mathematics education in the United States in mind. France is an existence proof for greater opportunities for teachers to engage in history of mathematics in this way.

In 1989, the National Council of Teachers of Mathematics (NCTM) issued the *Curriculum and Evaluation Standards for School Mathematics*. In the document, the NCTM listed "learning to value mathematics" as the first goal for students. The goal specified that

> Students should have numerous and varied experiences related to the cultural, historical, and scientific evolution of mathematics so that they can appreciate the role of mathematics in the development of our contemporary society and explore relationships among mathematics and the disciplines it serves .... It is the intent of this goal – learning to value mathematics – to focus attention on the need for student awareness of the interaction between mathematics and the historical situations from which it has developed and the impact that interaction has on our culture and lives. (NCTM 1989, pp. 5–6)

Equivalent recommendations concerning the role of the history of mathematics are found in the NCTM's *Principles and Standards for School Mathematics* (2000), with the objective of students developing an appreciation of mathematics as "being one of the greatest cultural and intellectual achievements of humankind" (p. 4). Unfortunately, this objective is couched in significantly weaker language[5] than that of the 1989 *Curriculum and Evaluation Standards* – that of developing an appreciation of certain historical and cultural attributes of mathematics as opposed to engaging in mathematics from multiple perspectives, including those along historical and cultural dimensions. In either case, there has not been overwhelming evidence that the goal or objective from either version of *Standards* is being achieved (Liu 2003, p. 418). When examining the record of conference sessions offered at NCTM annual meetings and published materials available through NCTM – particularly recent offerings – it is difficult to find evidence of the rhetoric of the 1989 and 2000 *Standards* calling for increased attention to the historical development of mathematics.

The important volume, *History in Mathematics Education: The ICMI Study* (Fauvel and van Maanen 2000), included a summary of what was known about the contribution of history of mathematics to the knowledge and perspectives of teachers and pupils. From a survey of the literature at the time, Barbin and her colleagues (2000) identified five distinct outcomes, including the ability of using history to promote changes in teachers' mathematical conceptions, the students' mathematical conceptions, the role of the teacher, the way students view mathematics, and the students' learning and understanding (p. 67). Whereas accounts exist that document each of these outcomes, Barbin was careful to observe the lack of the field's ability to document "the attainment of objectives claimed for using history" (p. 66) because large-scale assessments do not exist for such measures. Instead, qualitative methods are much more appropriate to ascertain whether using history in teaching mathematics can achieve what is claimed.

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[5] For example, in 1989, NCTM asked for students to have "numerous and varied experiences related to the cultural, historical, and scientific evolution of mathematics," which could have entailed learning mathematics from historical methods or reinventing such methods from guided explorations using historical problems. In 2000, however, the language was simplified to focus on the appreciation of mathematics.

24.3 History of Mathematics in Mathematics Teacher Education in the United States

In a similar manner, policy documents are used to impart standards on mathematics teacher preparation programs. In the United States, the jointly constructed National Council for the Accreditation of Teacher Education (NCATE) and the NCTM program standards, *Programs for Initial Preparation of Mathematics Teachers* (2003), described content standards[6] for seven mathematical strands at both the middle and secondary levels.[7] Consequently, for programs to achieve "National Recognition" under the NCATE model, "the program report must demonstrate that at least 80 % of all indicators are addressed and at least one indicator[8] is addressed for each standard" (NCTM 2007). The final indicator for each content standard called for teacher candidates to "demonstrate knowledge of the historical development of [topics] including contributions from diverse cultures" (NCATE 2003, p. 4).

The ability for a teacher education program to exhibit mathematics teacher candidates' history of mathematics content knowledge is important to achieve national recognition; however, mathematics teacher preparation programs may still achieve the status since only 80 % of indicators are needed for national recognition. This aspect of the program standards, which was aligned with the NCTM goal for students to develop an appreciation of the cultural and intellectual achievements represented in the development of mathematics, did serve to reinforce the argument that understanding and engaging in the study of the history of mathematics contributes to the mathematical and pedagogical preparation of mathematics.

In 2011, NCTM published its draft of the new initial certification program standards for middle- and secondary-level mathematics. Instead of one indicator within each of seven content standards dedicated to the provision that mathematics teacher candidates demonstrate knowledge of the historical development of particular mathematics content, the first draft of the standards asserted one indicator only. The proposed indicator appeared in Standard 6: Mathematics Teaching and Learning and was stated as, "Equity: Recognizing the cultural diversity that exists within classrooms, valuing the contributions of various cultures in the development of mathematics, and incorporating the historical development of mathematics and culturally relevant perspectives as tools to engage students" (NCTM 2011).

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[6] In the NCATE/NCTM program standards, "content standards" represent the different strands of mathematical knowledge teachers are responsible for knowing for teaching, such as knowledge of number and operation and knowledge of geometries.

[7] This is language of the NCATE/NCTM program standards, where "middle level" is understood as grades 6, 7, and 8 (pupils aged 12–14) and "secondary level" is understood as grades 9–12 (pupils aged 15–18). Many consider this redundant (including the author) since two divisions seem sufficient (e.g., elementary and secondary, or primary and secondary).

[8] In the NCATE/NCTM program standards, an "indicator" is a specific objective within a given content standard, such as, "Exhibit knowledge of the role of axiomatic systems and proofs in geometry" in the knowledge of geometries content standard.

After initial public response to the draft certification program standards for middle and secondary mathematics,[9] however, a new draft of the standards appeared in April 2012. In this draft as with the 2003 program standards, a final indicator was added to each of the content standards for middle and secondary mathematics. An example from middle-level algebra reads: "All middle grades mathematics teachers should be prepared to develop student proficiency with …[the] historical development and perspectives of algebra including contributions of significant figures and diverse cultures" (NCTM 2012). The current draft standards remained open for public comment until June 2012, and the final versions of the program standards were presented to the NCATE Specialty Area Studies Board in October 2012.

At the same time that the standards for mathematics teacher certification programs in colleges and universities in the United States are being rewritten, another influential document, *The Mathematical Education of Teachers* (or MET1, published in 2001) is also under revision. The draft of MET1 was published in early 2012 and public comment was accepted until the end of April 2012. MET1 (Conference Board for the Mathematical Sciences (CBMS) 2001) argued that prospective mathematics teachers could improve their knowledge of the history of mathematics as one way for them to "undertake, and then be able to challenge their students in ways that will lead them to reason and make sense of mathematics" (p. 99). Recommendations found in MET1 called for the inclusion of historical content in the preparation of both middle grades and high school mathematics teachers and focused on providing the means for prospective teachers "to develop an eye for the ideas of mathematics that will be particularly challenging for their students" (p. 126). The primary mode of preparation advocated in MET1 was in the form of undergraduate courses in teacher preparation programs. However, the recommendations articulated in MET1 were not intended to outline potential routes for taking non-university level courses. Instead, the intention was that institutions of higher learning would develop programs and courses to meet the needs of teacher candidates within their own context while attending to the recommendations in MET1.

The role of history of mathematics in secondary mathematics teacher preparation is also strongly articulated in *The Mathematical Education of Teachers II* (MET2) (CBMS 2012). MET2 suggests that preparation programs for middle grades teachers include 24 semester hours of mathematics courses, some of which are courses to "strengthen prospective mathematics teachers' knowledge of mathematics and broaden…understanding of mathematical connections…" (p. 46). Furthermore, the writers claimed that "a history of mathematics course can provide middle grades teachers with an understanding of the background and historical development of many topics" (p. 48).

A course in history of mathematics is identified in MET2 as essential for future high school mathematics teachers:

> The history of mathematics can either be woven into existing courses or be presented in a course of its own. In both instances, it is important that the history be accurate; instructors

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[9] Although many consider middle grades mathematics to be included in "secondary," these are the terms that NCTM uses.

> who have no contact with historians need to be aware that findings from historical research may contradict popular accounts…. It is particularly useful for prospective high school teachers to work with primary sources. Working with primary sources gives practice in listening to "wrong" ideas. Primary documents show how hard some ideas have been, for example, the difficulties that Victorian mathematicians had with negative and complex numbers helps prospective teachers appreciate how hard these ideas can be for students who encounter them for the first time.
>
> Finally, primary documents exhibit older techniques, and so give an appreciation of how mathematics was done and how mathematical ideas could have developed. (CBMS 2012, pp. 61–62)

MET2 also recognized the role of additional study in the history of mathematics for those preparing to teach high school mathematics:

> Many topics in the history of mathematics are closely related to high school mathematics, for example, history of statistics, history of trigonometry, and history of (premodern) algebra. It is important to make sure that the materials used for courses on these topics include a significant amount of mathematical content. (CBMS 2012, p. 67)

At the time of the writing of this chapter, however, the 2003 NCATE program standards were still in place, and substantial diversity exists among mathematics teacher preparation program requirements in the United States and as to whether a course on the history of mathematics should be included in such programs. For example, many programs do not include a separate history of mathematics course since programs can still be accredited by NCATE without specific attention to the historical development of mathematics. It is also possible for institutions to elect to not pursue program accreditation through the organization. Instead, teacher preparation programs within colleges and universities may opt for state accreditation only or follow other accreditation standards, such as those of the Interstate Teacher Assessment and Support Consortium (InTASC).

Alternatively, mathematics teacher preparation programs offer history of mathematics as an elective, with such courses often focusing more on the mathematical content and less on the cultural, philosophical, historical, and pedagogical elements. Still other programs, such as the UTeach program at the University of Texas at Austin, as well as its 34 replication sites, require that prospective mathematics teachers take "Perspectives on Science and Mathematics"[10] with fellow prospective science teachers.

In an effort to describe the extent to which mathematics teacher preparation programs include history of mathematics, information provided by universities and colleges was used to survey mathematics teacher preparation programs for their requirement (or not) of a history of mathematics course.[11] Two sources of information were used. First, a search using the Carnegie Foundation for the Advancement of Teaching (http://classifications.carnegiefoundation.org/lookup_listings/institution.php)

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[10] The number of replication sites as of May 2013. Also, since faculty called upon to teach "Perspectives" are often historians of science, the course privileges a "history of science" perspective. Consequently, the breadth of the historical implications of school mathematics or nature of mathematics that students take away from such a course is in need of further research.

[11] I am grateful to Christopher Thompson, my graduate research assistant, for his invaluable assistance in collecting and analyzing this information in 2011.

returned a data set of 1713 universities or colleges whose basic classification was either (1) a research (doctoral degree granting) university (RU/VH, RU/H, or DRU)[12] or (2) a university that offered master's degrees (L, M, or S)[13] or (3) a university or college that offered only bachelor's degrees.

Next, the set of 1713 institutions were stratified by state (including the District of Columbia), and the indicator function *I* was composed with a value of "1" indicating that the institution included a mathematics education program and a value of "0" for those institutions not offering a mathematics teacher preparation program.[14] Institutions that offered a degree program in mathematics education were determined from searching the CollegeBoard (http://collegesearch.collegeboard.com/search/index.jsp) College MatchMaker database[15] and selecting the categories of "Education" and then "mathematics education" as search criteria. The search returned 569 institutions. Although a large-scale survey (of these 569 institutions) would have been optimal, the goal was to provide a snapshot of whether mathematics teacher preparation programs required or even offered a history of mathematics course. Consequently, institutions were randomly selected from the stratified sample (N = 569) – three institutions from each state and the District of Columbia, which constitutes one each corresponding to the three types of institutions according to the Carnegie levels (doctoral, master's, bachelor's).

The results of the survey revealed that of 153 potential institutions, the stratified random sample returned only 15 that did not offer a mathematics teacher preparation program meeting the criteria. Of the remaining sample, 62 programs representing 37 states required a history of mathematics course for their program. Also variable was the number of institutions that offered elective or optional history of mathematics courses – or no course at all – as well as whether the mathematics teacher preparation programs were housed in education or mathematics departments.

The United States is not alone in the variety of ways in which recommendations to include history of mathematics in mathematics teacher preparation programs are implemented. Elsewhere, there is evidence of a wide variety of established practices with regard to the role of the history of mathematics in the preparation of mathematics teachers.[16] In *History in Mathematics Education: The ICMI Study* (Fauvel and van Maanen 2000), an entire chapter was dedicated to the presence of history of mathematics in programs for trainee (i.e., prospective) teachers.

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[12] The Carnegie basic classifications are RU/VH = Research Universities (very high research activity); RU/H = Research Universities (high research activity); DRU = Doctoral/Research Universities.

[13] These Carnegie basic classifications are Master's L = Master's Colleges and Universities (larger programs); Master's M = Master's Colleges and Universities (medium programs); Master's S = Master's Colleges and Universities (smaller programs).

[14] Only initial teacher certification programs at the undergraduate level were considered.

[15] CollegeBoard College MatchMaker database (http://collegesearch.collegeboard.com/search/index.jsp) was last accessed on 10 October 2010. The database has been replaced with a much more student-friendly website, BigFuture (https://bigfuture.collegeboard.org/), last accessed 27 December 2012.

[16] For the purposes of this chapter, we only consider initial teacher preparation programs, that is, undergraduate (tertiary) at the university or college level or postgraduate programs.

24.4 History of Mathematics in Mathematics Teacher Education Around the World

In the 2000 ICMI Study, Schubring and colleagues (2000) described the state of history of mathematics for teachers in the world based upon information available at the end of the twentieth century. In addition to accumulating prior views and documenting prominence of history of mathematics in mathematics teacher education, the authors described the "state of teaching history of mathematics to future mathematics teachers" (Schubring et al. p. 94) within several countries considered to be "a fairly representative sample" (Schubring et al. p. 94). Schubring and his colleagues also claimed that whereas history of mathematics in the mathematical education of any person pursuing a degree in mathematics was once more commonly found in locations where there existed "an extended tradition in mathematics history and a considerable mathematical community" (Schubring et al. 2000, p. 94), this was no longer the case.

Gathering information about cases beyond those available at the time of the ICMI Study proves difficult, however. For example, several attempts to contact those with keen interest in the history and pedagogy of mathematics (HPM) in 2012, particularly with regard to the role of HPM in mathematics teacher education, were left unanswered. In another attempt to gather such information at the International Congress on Mathematical Education (ICME) in Seoul, South Korea, in July 2012, it became apparent that many locations around the globe struggle with incorporating such courses in mathematics teacher education programs.

Schubring and his colleagues (2000) identified a wide variety of examples of the extent to which a historical component was a part of preparation of mathematics teachers. To facilitate the discussion of differences, they divided the examples (by country) into three types[17]: countries with smaller mathematical communities but which experienced success in establishing strong records in teaching history of mathematics, countries with a longer tradition of research and teaching in mathematics history but which struggle with establishing a historical component within mathematics teacher education programs, and countries on the "periphery."[18] So as not to repeat the work of Schubring and colleagues, examples of what is most recently known about the role of history of mathematics in mathematics teacher education in several different contexts are described here for a small sample of countries around the world.

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[17] Only European countries were discussed in the analysis with regard to the first and second types of country identified in the ICMI Study.

[18] The ICMI Study defined countries on the periphery as those "where, comparatively recently, historians of mathematics, or mathematics educators with a strong interest in mathematics history, have achieved an academic position where they are able to introduce mathematics history courses into teacher training" (Schubring et al. 2000, p. 94).

24.4.1 Europe

At the Sixth European Summer University in Vienna in 2010, a panel was held on "The Role of the History and Epistemology of Mathematics in Teachers Training" (Barbin et al. 2011). Each panelist discussed the current status of both pre-service and in-service mathematics teacher education in their country. Barbin detailed the situation in France, which has always been considered to have a strong focus on history and epistemology in teacher training. Until 2010, the training of prospective mathematics teachers took place at each University Institute for Teachers Training (IUFM). Examples of the training for teachers that took place at the institutes included a 30-h course comprised of content in the history of mathematics. Currently, all future teachers must obtain a master's degree, and the course of study includes history and epistemology of mathematics.[19]

In Italy, as is the case in many other locations, primary teachers teach mathematics along with other subjects and obtain their university degree in an educational department, and there are no formal courses on history of mathematics. Although some university programs do include history of mathematics as components of other courses, this practice is not standardized. Secondary teachers who will teach lower secondary mathematics (to pupils aged 11–14) obtain a degree in science, mathematics, physics, or chemistry. Those who will teach upper secondary mathematics (to pupils aged 14–19) are required to obtain a degree in mathematics or physics. Italy enjoys a long tradition of a community of mathematicians who share a strong interest in primary and secondary school teaching. Furinghetti reported that "for about the last 50 years, the curriculum of mathematics in Italian universities encompasses special courses addressed to prospective teachers" (Barbin et al. 2011, p. 28); the content of some of these courses includes history of mathematics.

Austria[20] has a strong tradition of requiring history of mathematics course work for prospective teachers; it is a compulsory course at two of the country's seven universities and either an elective or optional course at five universities. Table 24.1 displays the seven universities and the category of requirement applicable to each. Regardless of level of requirement, course lecturers are free to construct a course in the history of mathematics as they choose.

24.4.2 Africa

The Moroccan situation is an example of the changing role of history of mathematics within the preparation of prospective mathematics teachers. Previously, the training of teachers was under the direction of specific educational institutes that were mainly involved with the educational and didactical dimensions of pre-service

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[19] There exists variability in the importance placed on teaching these subjects in France.

[20] The author is grateful to Manfred Kronfellner for providing this information.

Table 24.1 Types of history of mathematics courses in Austria: compulsory, elective, or optional

University	Required	Elective or optional[a]
University of Innsbruck	Compulsory course, lecture, with final examination	
University of Klagenfurt	Compulsory course, seminar, with immanent assessment	
Vienna University of Technology		Elective course, lecture
University of Vienna		Elective course, lecture
Johannes Kepler University of Linz		Elective course, seminar
University of Salzburg		Elective course, lecture, and seminar combination
University of Graz		Optional course, when available

[a] "Elective course" means that history of mathematics is one of several courses students must select from a collection of options. They must select a certain number of elective courses from the collection, but they do not have to select all in their course of study. An "optional course" may not always be available as an elective option

teacher training. Consequently, the history of mathematics held a reduced role and was evoked during the study and didactical analysis of concepts. A few exceptions existed. For example, in the *École Normale Supérieure* of Marrakech, courses on the history and philosophy of mathematics were always taught. Currently and according to the new reforms in Morocco, the training institutes for prospective secondary teachers were moved to universities. This aspect of the reforms enables universities to organize and implement courses for prospective teachers and, as a result, aids in providing more substantial pedagogical training of teachers. In 2012 prospective teacher training programs were under revision, and those involved with the work are hopeful that the historical and cultural dimensions of mathematics will receive particular attention and that such dimensions will help develop and reinforce learning of scientific concepts, citizenship, and critical thinking of students.[21]

24.4.3 Asia

Whereas much of the Western world seeks to increase attention to mathematical contributions of non-Western cultures in history of mathematics courses (and history of mathematics courses for prospective mathematics teachers), a similar phenomenon occurs in many Asian contexts. In many Asian countries there are efforts to highlight Western developments and to compare them with methods, algorithms, and examples found in ancient texts and manuscripts. However, well-developed courses or units within courses in mathematics teacher preparation programs are still absent, as in

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[21] The author is grateful to Abdellah El Idrissi for providing this information.

the case of South Korea.[22] A trend that may prove to be influential in the near future is the increased attention to history of mathematics in the preparation of mathematics teachers in South Korea (and other proximal countries), especially after the introduction of the International Study Group on the Relations between the History and Pedagogy of Mathematics (HPM Group) to several mathematicians and mathematics teacher educators as a result of HPM 2012 in Daejeon.

24.5 Development of Theoretical Claims: Why Use History in Teaching Mathematics

Although there has been strong interest in the question of how history of mathematics benefits teachers and learners of mathematics since the 1890s (Fasanelli 2001), significant international activity directed at addressing the question began in the 1970s. Key to this activity was the creation of the International Study Group on the Relations between the History and Pedagogy of Mathematics (HPM Group), which was officially established as a satellite group of the International Congress on Mathematical Education (ICME) in 1972. Henk Bos, Barnabas Hughes, Phillip Jones, Leo Rogers, and Roland Stowasser were among the group of mathematicians, mathematics historians, and mathematics educators gathered at the first sessions held in association with in 1976 at ICME-3 in Karlsruhe, Germany. As a result of these initial sessions, the HPM Group was established and the official aims of the Study Group were established. The group sought to:

1. Promote international contacts and exchange information concerning:
    (a) Courses in history of mathematics in universities, colleges, and schools
    (b) The use and relevance of history of mathematics in mathematics teaching
    (c) Views on the relation between history of mathematics and mathematical education at all levels
2. Promote and stimulate interdisciplinary investigation by bringing together all those interested, particularly mathematicians, historians of mathematics, teachers, socialscientists, and other users of mathematics
3. Encourage a deeper understanding of the way mathematics evolves and the forces that contribute to this evolution
4. Relate the teaching of mathematics and the history of mathematics teaching to the development of mathematics in ways that assist the improvement of instruction and the development of curricula
5. Produce materials that can be used by teachers of mathematics to provide perspectives and to extend critical discussion of the teaching of mathematics
6. Facilitate access to materials in the history of mathematics and related areas
7. Promote awareness of the relevance of the history of mathematics for mathematics teaching in mathematicians and teachers

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[22] The author is grateful to Sang Sook Choi-Koh for describing the South Korean context.

8. Promote awareness of the history of mathematics as a significant part of the development of cultures (Fasanelli 2001, p. 2)

The influence of the articulated aims can be found in the preponderance of theoretical literature published during the first 25 years of the existence of the HPM Group. For example, Fauvel (1991) provided a list of 15 reasons that are used to promote using history in mathematics education:

> … helps to increase motivation for learning; gives mathematics a human face; historical development helps to order the presentation of topics in the curriculum; showing pupils how concepts have developed helps their understanding; changes pupils' perceptions of mathematics; comparing ancient and modern establishes value of modern techniques; helps to develop a multicultural approach; provides opportunities for investigations; past obstacles to development help to explain what today's pupils find hard; pupils derive comfort from realizing that they are not the only ones with problems [with mathematics]; encourages quicker learners to look further; helps to explain the role of mathematics in society; makes mathematics less frightening; exploring history helps to sustain [teacher] interest and excitement in mathematics; and provides opportunity for cross-curricular work with other teachers or subjects. (Fauvel 1991, p. 4)

In the current educational context that often includes a heightened emphasis on standards and high-stakes accountability, many of Fauvel's reasons are easy to ignore – particularly if educators perceive the actions of the proposed reasons to not be aligned to content and practices of the curriculum or assessments. Examining one reason as an example, most mathematics teachers agree that "showing pupils how concepts have developed" may have a role in pupils' understanding of particular mathematical concepts (e.g., operations with integers, complex numbers). However, mathematics teachers may be skeptical that employing historical methods to show this to pupils is a viable pedagogical tool.

Furinghetti (2002) observed that history can be used "as a mediator to pursue the objectives of mathematics education" (Abstract). Furthermore, Furinghetti proposed that enabling students to work with topics at an informal level before formally investigating topics was similar to Freudenthal's view that contextual problems provide efficient opportunities to allow formal mathematics to emerge. In this way Furinghetti claimed using "history may reveal itself fruitful and [a] sense-carrier" (p. 3).

There is important evidence that the membership and interested colleagues of the HPM Group are making progress towards achieving many of the official aims. Not only do the Topic Study Groups of the International Congress meetings (since 1972) and the HPM Satellite meetings produce peer-reviewed, published proceedings, but the European Summer University on the History and Epistemology in Mathematics Education meetings (now held every 2 years, not including the years in which the ICME and HPM Satellite meetings are held)[23] and now a working group of the Congress of the European Society for Research in Mathematics Education (CERME)

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[23] The European Summer University on the History and Epistemology in Mathematics Education (ESU) was held every 3 years from 1993 until 2010. Subsequent ESUs will be held every 4 years (e.g., the Seventh ESU will be in 2014), but not in years when ICME meetings are held.

since 2009 also add "substantially to the amount of papers on history in mathematics education" (Jankvist 2012, p. 296). Moreover, special publications have appeared as a result of increased attention to the inclusion of history of mathematics in mathematics education. Among these are several books published by The Mathematical Association of America (e.g., *Using History to Teach Mathematics: An International Perspective* (Katz 2000), *Recent Developments on Introducing a Historical Dimension in Mathematics Education* (Katz and Tzanakis 2011)) and other important volumes such as *History in Mathematics Education: The ICMI Study* (Fauvel and van Maanen 2000) and *Crossroads in the History of Mathematics and Mathematics Education* (Sriraman 2012).[24]

Even with this increased attention, however, many contributions to these edited volumes are what Siu and Tzanakis referred to as "propagandistic" (2004, p. vii); that is, it is evident that a critical mass of teachers and scholars alike attest to the worthiness of history in mathematics education. As a result, such contributions remain theoretical as opposed to providing empirical results of what happens when history of mathematics is part of the instructional program. The proportion of contributed chapters in such volumes that are focused on history of mathematics in mathematics teacher education is also a concern. For example, in Katz and Tzanakis (2011), only four of 24 chapters were devoted to this theme and none of the 25 chapters in Sriraman (2012) were.

One possible reason for the abundance of theoretical descriptions of the importance of using history of mathematics in teaching is the obstacle of adequately preparing primary and secondary mathematics teachers to use the history of mathematics in meaningful ways in their teaching. Jones (1969) claimed, "the history of mathematics will not function as a teaching tool unless the users (1) see significant purposes to be achieved by its introduction, and (2) plan thoughtfully for its use to achieve these purposes" (p. 5). Although Jones' claims were made over four decades ago, most mathematics teacher educators would find it difficult to summarize two key issues more succinctly. Furthermore, many argue that the lack of opportunity for history of mathematics course work in mathematics teacher preparation programs – whether primary or secondary – is intimately connected to the lack of strong mathematical knowledge of teacher candidates.

Finally, it is important to keep in mind that a "domino effect" may be at work here. For example, it may be difficult to identify literature describing accounts of elementary and secondary teachers incorporating history of mathematics in their mathematical instruction because of the absence of history of mathematics in mathematics teacher education.

The remainder of this chapter discusses a variety of empirical investigations that establish a premise for why so many advocate for the inclusion of history of mathematics in teaching and that motivate future investigations. First, and because the focus of the chapter is on the role of history of mathematics in mathematics teacher education, studies about the influence of studying history of mathematics on prospective primary and secondary mathematics teachers are described. Next,

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[24] For a more comprehensive list, see Jankvist (2012).

accounts of the ways in which teachers – having previously studied history of mathematics to some extent – incorporate history of mathematics in their teaching are presented.

24.6 History of Mathematics in Primary Mathematics Teacher Education

The lack of guidelines that call for history of mathematics in primary mathematics teacher[25] education programs around the world makes it difficult to identify empirical investigations that involve this population. Exemplars of empirical work conducted with prospective primary mathematics teachers tend to focus on attitudes and beliefs. Primary mathematics teacher preparation programs vary in number of hours, courses, seminars, or lectures in both mathematics content and pedagogy (i.e., didactics). Additionally, primary mathematics teacher education programs typically prepare teachers responsible for multiple subject areas – and often for all academic and specialty areas (e.g., art, music). Secondary mathematics teacher education programs, however, focus on preparing teachers of mathematics and in some cases, a second subject area. Consequently, when and how history of mathematics is employed in the preparation of primary mathematics teachers varies. Much of this variability may result from program expectations for the mathematics content required for prospective primary teachers compared to the content expectations for prospective secondary teachers.

24.6.1 First Example

Fleener and colleagues (2002) studied the influence of a mathematics education curriculum that incorporated historical topics in each of three different courses on prospective elementary mathematics teachers' "meaning-making efforts" (p. 73). A series of questions were asked of prospective teachers in three courses, representing three different time points in their teacher preparation program: a mathematics course required for elementary education majors taken early in the second year of the elementary education program, the first mathematics education teaching and learning course, and the mathematics methods taken in the last semester before the teaching internship. The extent of history of mathematics in each course is given in Table 24.2.

The researchers collected responses to a variety of prompts about prospective elementary teachers' experiences with history of mathematics during the three courses.

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[25] In general, the terms "primary mathematics teachers" and "elementary mathematics teachers" are used interchangeably to describe teachers of pupils aged 5–11 years of age. And, regardless of the term used, such programs are those that prepare generalists, or teachers who teach most if not all of the academic subjects.

Table 24.2 Course descriptions (Fleener et al. 2002)

Course description	When taken	History content
MATH 3213: General mathematics course ($n=48$)	Second semester of second year of elementary mathematics education program	Students conduct research on a topic from the history of mathematics, write a two-page paper, and deliver a brief presentation in class
EDMA 3053: First mathematics education teaching and learning course ($n=37$)	After admission to teacher education program (typically in the third year of a 4-year program)	Students conduct research on a historical figure or historical topic, write a formal paper, and prepare a one-page handout to accompany a presentation delivered to the class. "Students are required to develop activities for elementary students that incorporate an inquiry approach using historical topics or individuals" (Fleener et al. 2002, p. 75)
EDMA 4053: Math methods ($n=12$)	Last semester of course work (taken just before teaching internship)	Content includes: Select a mathematician, conduct research, role-play their mathematician Tested on historical contributions, significance of historical figures, and topics on midterm exam Discussions, readings, and activities to encourage planning of historical activities in future teaching

The prompts asked for prospective teachers to reflect on how learning about the history of mathematics affected their understanding of mathematics and how the preparation of their report on a historical topic or figure aided in understanding mathematics and strategies for teaching mathematics. The participants were also asked about their experiences after participation in each course, including whether they retained handouts from any peers' historical topic presentation or whether they used ideas from their own or others' presentations when preparing classroom activities.

In the analysis of the data, Fleener and her colleagues (2002) were interested in which orientation towards learning mathematics each prospective teacher favored. In particular, they examined participant responses for evidence of knowledge informed by the technical, practical, or emancipatory interests. Grundy (1987) defined the technical interest as "a fundamental interest in controlling the environment through rule-following action based upon empirically grounded laws" (p. 12): the practical (or, hermeneutical) interest as "a fundamental interest in understanding the environment through interaction based upon a consensual interpretation of meaning (p. 14), and the emancipatory (cognitive) interest as "a fundamental interest in emancipation and empowerment to engage in autonomous action arising out of authentic, critical insights into the social construction of human society" (p. 19).

Fleener and colleagues (2002) found that the prospective elementary teachers favored a technical perspective when studying history of mathematics for their own learning and for use in teaching. They also claimed that real-life experiences and historical connections may not equip future teachers with necessary tools to overcome long-held traditional beliefs about mathematics and mathematics learning, and that the prospective teachers in the study were over-reliant on algorithms, which in turn prevented them from exploring deeper meanings within mathematics. Although Fleener and her colleagues (2002) claimed that "critical and historical approaches, even sustained over several semesters of mathematics instruction, are not sufficient for students to develop an emancipatory approach" (p. 80), it is possible that the orientation of the history of mathematics instruction in the three courses favored a technical perspective as well.

Details about the topics or mathematicians that the prospective teachers selected for their research or the content of focus during the mathematics methods course were not provided by the authors, and consequently, it is difficult to further interpret the outcomes they discussed. In research where more details are provided about historical content, potential solutions to improve the ways in which history of mathematics is incorporated in the preparation of primary mathematics teachers are easier to identify, as in the case of Charalambous et al. (2009).

24.6.2 Second Example

Charalambous and colleagues (2009) quantitatively described how prospective primary mathematics teachers' attitudes and beliefs were impacted as a result of participating in a teacher preparation program that contained two content courses grounded in the history of mathematics. The courses, designed and implemented at the University of Cyprus, have been in place for more than a decade. Each three-credit-hour course lasted 13 weeks was taken consecutively, and together the courses were considered the only mathematics-oriented courses in the program for the prospective primary mathematics teachers.

There were 94 prospective primary mathematics teachers who were surveyed four times (pre- and post-surveys for each of the two courses), and six participants (a convenience sample) were interviewed for additional insight after quantitative results were compiled. The authors divided the participants into two groups, according to their acceptance into the pre-service teacher program at the University of Cyprus. The first group ("G1" in the study, with 52 participants) opted to take the mathematics entrance examination and the second ("G2," with 42 participants) did not.[26]

The authors reported that in many ways, the survey results pointed to the finding that the two courses grounded in the history of mathematics were a failure. For example, "the G2 participants exited the program with increased negative attitudes toward mathematics" (Charalambous et al. 2009, p. 177). And G2 participants were unable to "see many connections between the content and the activities of the two

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[26] At the University of Cyprus, entrance into the preservice teacher program is highly competitive and students must take four entrance exams: one in language and three others in different subject areas of their choice.

courses and the content considered in elementary grades" (Charalambous et al. 2009, p. 177). Each of these results counters much of the rhetoric about why history of mathematics should be used in teaching mathematics. Consequently, the authors used interview data to aid in understanding the quantitative results. They found that the teacher candidates shared that their previous mathematical experiences were all too common, namely, that such experiences "did not help [them] learn how to think" (p. 174) – but merely honed their test-taking skills.

An important outcome from Charalambous and his colleagues (2009) is the identification of three limitations in the approach employed – all of which may serve future research and development of mathematics teacher education programs well. First, they recognized that not sharing the intention to ground the two courses in history of mathematics was a mistake. Second, the authors anticipated that an elementary teacher preparation program grounded in the history of mathematics would impact the participants in such a way that they would begin to view mathematics differently than they did before studying at university. Unfortunately for many of the pre-service teachers, their experiences with the two courses were too similar to their prior experience with learning mathematics: that certain complex mathematical problems were challenging and stressful and the grounding in history failed to matter in a positive way. Lastly, opportunities to genuinely experience the development of mathematics were insufficient for the six participants interviewed. Indeed, this is one of the most challenging issues with implementing history of mathematics in teacher preparation programs. Even with careful planning, knowledgeable instructors, and appropriate resources, such a course can still feel as a whirlwind of historical activity, punctuated by (in the case of many of the G2 participants) difficult mathematical ideas and methods.

Finally, there are three cautions provided by Charalambous and colleagues (2009) that must be heeded when considering similar experiences for future primary mathematics teachers. First, the decision to implement a content course for prospective mathematics teachers grounded in the history of mathematics should be shared with them. Perhaps the most important reason for this is that their prior experience with history of mathematics may be limited, and predetermined attitudes towards mathematics may serve as an obstacle for learning in the course. Second, the difficulties prospective teachers experience with the content of courses based upon the history of mathematics "need to be acknowledged and addressed" (p. 178). And third, to prevent spending insufficient time on the evolution of key mathematical ideas, the authors suggested designing "guided explorations of important mathematical ideas that will support pre-service teachers in their work of teaching" (p. 178). Furthermore, the authors recognized the potential for history of mathematics in teacher education program to contribute to the development of knowledge "that is both useful and usable for the work of teaching mathematics" (p. 179). An important means to this end is the identification of the content of the two courses Charalambous and colleagues (2009) implemented (Table 24.3).

The content of the second course identified by Charalambous and his colleagues (2009) raises an additional concern. Many of the topics identified are well beyond the content that many prospective primary mathematics teachers are familiar with,

Table 24.3 Topics for courses grounded in history of mathematics: Charalambous et al. (2009, p. 179)

Course	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
First course	First arithmetic systems Arithmetic systems with/without zero Contemporary place value system Two methods multiplication	Transition to systematic proof Applications of similar triangles Different proofs of the Pythagorean theorem Pythagorean mathematics Applications of Pythagorean mathematics in elementary school	Three famous problems of antiquity Attempts to solve the problems (and their contribution to the expansion of mathematical knowledge)	Euclid and his contributions to mathematics	Contribution of other renowned mathematicians (Archimedes, Apollonius, Pascal)
Second course	Zeno's paradox and the principle of exhaustion Development of the notion of limits Limits, differentiation, integration (including applications in real-life situations) Contribution of Newton and Leibniz to modern mathematics	The liberation of geometry: Attempts to prove the 5th Euclidean axiom When is the sum of the angles of a triangle not equal to 180°? Bolyai and Lobachevsky and the development of hyperbolic geometry Riemann and elliptic geometry	The liberation of algebra: Peacock's contribution Hamilton and his quaternions Cayley and matrix algebra Applications in real-life situations	Sets and binary relationships: Notion of sets and associated paradoxes Operations on sets and their properties Cartesian product and its applications to elementary school	A sample of more advanced mathematics: Mathematical logic and applications Boolean algebra Computers and mathematics

and as a result, whatever knowledge prospective mathematics teachers are expected to gain through history of mathematics may not be seen as useful and usable for the work of teaching mathematics. The design of such courses cannot ignore the importance of topics most associated with the work of future primary teachers.

24.6.3 Third Example

In an effort to establish a reliable instrument to measure attitudes and beliefs towards using history of mathematics in teaching, Alpaslan and colleagues (2011) constructed, administered, and evaluated the underlying factor structure of their instrument, *Attitudes and Beliefs towards the Use of History of Mathematics in Mathematics Education Questionnaire*. The instrument was constructed from a variety of available survey questions and was administered to a purposive sample[27] of 237 pre-service primary mathematics teacher candidates in 2010–2011. The authors conducted factor analysis and identified three factors "by considering the field of history in mathematics education and…instrument development studies about social sciences" (Alpaslan et al. 2011, p. 1666): positive attitudes and beliefs towards the use of history in mathematics education, negative attitudes and beliefs towards the use of history in mathematics education, and self-efficacy beliefs towards the use of history in mathematics education. After problematic items were removed from the instrument, the same validity and reliability analyses were conducted again. The final survey contains 35 items; 22 items are included in the positive attitudes and beliefs component, nine items are contained in the negative attitudes and beliefs component, and four items are contained in the self-efficacy component.

The instrument developed by Alpaslan and his colleagues suggests important opportunities for future empirical work in the field of history in mathematics education. As they posited:

> … the results gained by using the instrument by future research projects would have valuable implications for teacher educators in different universities, education policy makers and curriculum developers of different countries in designing curriculum for mathematics education [at] different levels. (Alpaslan et al. 2011, p. 1669)

Furthermore, research regarding the problematic trends in prospective teachers' beliefs about mathematics and attitudes towards learning mathematics via the history of the important development ideas revealed by Charalambous and colleagues (2009) would also be informed by use of the instrument on a larger scale. For example, pre- and post-administrations of the instrument have the power to "reveal potential effects of interventions on the attitudes and beliefs towards the teaching approach in question" (Alpaslan et al. 2011, p. 1669). Future use of the instrument

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[27] In qualitative research, a purposive sample is one in which a particular participant population is targeted, especially when there is a special nature of the study or participants are difficult to find. This was the case of Alpaslan's and his colleagues' research, where new reforms were in place in Turkey's higher education institutions.

can help reveal gaps in learning and knowing mathematics for teaching and will enable researchers to investigate ways in which history of mathematics may fill such gaps. Furthermore, the populations available to use the instrument are extensive, including pre-service teachers, in-service teachers, and with further development and modifications, primary school pupils.

24.6.4 Fourth Example

Certainly an abundance of empirical studies that rely upon survey data – and thus, self-report data – is a concern for the field of history in mathematics education. Although survey data provide important descriptive information about the research questions posed and establish the landscape of future research directions, the field requires rigorous and extensive empirical study. One promising study, proposed by Alpaslan and Haser (2012), will "provide…teacher educators with possible effective presentations of the history of mathematics knowledge for teaching mathematics" (p. 2). In the pilot study they described, Alpaslan and Haser will conduct a case study on the implementation of a "History of Mathematics" course for lower secondary prospective mathematics teachers (who will be trained to teach 6th, 7th, and 8th grade mathematics in Turkey).

In their future research Alpaslan and Haser (2012) plan to investigate the extent to which the history of mathematics content within the course is used both "as a tool" and "as a goal" (Jankvist 2009) in the course. Furthermore, they will examine whether the content of the history of mathematics course will be addressed from an illumination approach, module approach, or history-based approach (Jankvist 2009). Finally, Alpaslan and Haser will describe how the course content and experiences are reflected in the instructor's and prospective teachers' views.

The results of the study can prove promising for several reasons. First, the researchers plan for multiple data sources, including "observation of the natural course process, content, tasks, and experiences, the nature of the content-related communication between the pre-service teachers and the instructor, and the participation of pre-service teachers in the course experiences" (Alpaslan and Haser 2012, p. 3). A study on the impact and results from implementing a history of mathematics course in mathematics teacher education has not yet been treated to the extent proposed here.

Second, the potential to inform the construction or modification of courses in the history of mathematics for prospective teachers (particularly for future teachers of upper elementary and lower secondary pupils) as a result of the pilot and full-scale study is extensive. Whereas the topics of the two-course sequence implemented by Charalambous and his colleagues (2009) represent an important contribution, Alpaslan and Haser's (2012) investigation has the potential to produce a substantial publication outlining solutions to several obstacles regarding the construction, implementation, and outcomes of history of mathematics courses for prospective mathematics teachers.

Finally, Alpaslan and Haser (2012) will use Jankvist's (2009) recent and influential distinctions of "hows" and "whys" as a framework[28] for the research questions, data collection, and data analysis. The attention to considering these distinctions in investigations such as the study being conducted by Alpaslan and Haser continues to strengthen the field of history in mathematics education. The working group on "History in Mathematics Education" at the seventh Congress of the European Society for Research in Mathematics Education (CERME-7) identified several key issues as crucial for the domain of history in mathematics education, including:

> the need for developing theoretical constructs that provide some order in the wide spectrum of research and implementations done so far; to somehow check the efficiency of introducing a historical dimension; and to develop appropriate conditions for designing, realizing, and evaluating our research…. (Jankvist et al. 2011, p. 1636)

Thus, in an effort to connect content from a history of mathematics course to the extent in which tools, goals, and approaches are addressed – as well as what such content and experiences mean for developing prospective mathematics teachers – Alpaslan and his colleagues may in fact develop a research agenda that informs each of the key issues for the field.

24.6.5 Summary

This section discussed four studies pertaining to the role of history of mathematics in primary mathematics teacher education. Certainly this is not a comprehensive description of literature on research about the effect (e.g., attitudes and beliefs) or inclusion (e.g., history of mathematics courses or content within teacher preparation programs) of history of mathematics. However, there is an abundance of survey research focused on the topic in primary mathematics teacher education and to include additional descriptions is an exercise in repetition.

To be fair, extensive variability exists with respect to programs preparing future primary mathematics teachers. In the United States alone, a key variable is the mathematics content required of these future teachers. For example, it is not uncommon for primary teacher preparation programs to require only one or two lower division[29] mathematics courses for prospective elementary education candidates. In other programs, however, and in some cases for every elementary teacher preparation program in a given state in the United States, a sequence of "Mathematics for …" courses are required for those preparing to teach elementary school.[30]

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[28] The influence of Jankvist (2009) has been extensive; see examples in Clark (2011), Kjeldsen and Blomhøj (2009), and Tzanakis and Thomaidis (2011).

[29] Lower division courses are courses taken during the first and second year at universities and colleges in the United States.

[30] In the United States, Maryland represents an example of this. Prospective elementary teachers are required to take a sequence of mathematics courses, though these may vary by institution.

The variability in mathematics course requirements for prospective elementary mathematics teachers may be the cause for the limitation of literature (either descriptive or empirical). For those preparing to teach secondary mathematics, a wide range of preparation programs also exists. However, the number of mathematics courses necessary for teaching mathematics at the secondary level (e.g., to pupils aged 12–18) is typically greater than that required for elementary teachers. Consequently, there are an increased number of possibilities within a teacher preparation program of which history of mathematics can be part.

24.7 History of Mathematics in Secondary Mathematics Teacher Education

In this section a representation of both theoretical work about and empirical studies conducted with prospective secondary mathematics teacher populations are discussed. For ease in presentation, the studies are divided into two types. First, descriptions of the perceptions of history of mathematics that is part of a teacher preparation course are given, where the influence of history of mathematics is primarily the "story" of mathematics. Secondly, examples of research are given in which the history of mathematics influenced prospective teachers' mathematical knowledge, as a result of an experience in history of mathematics as part of a teacher preparation program.[31]

24.7.1 History of Mathematics: Influences of Telling the "Story" of Mathematics

Many examples of published research literature in the field of history in mathematics education describe experiences in the history of mathematics for those preparing to teach secondary mathematics. Of these there are two main types of contributions. A large proportion of published accounts describe prospective teachers' attitudes towards history of mathematics or using history of mathematics in teaching, as was the case with research involving prospective elementary mathematics teacher populations. A second type[32] of contribution explains results anecdotally, punctuated by comments from students enrolled in the course.

At the University of Maryland, Baltimore County, for example, prospective teachers take Statistics, Mathematics for Elementary Teachers I, and Mathematics for Elementary Teachers II.

[31] In some contexts the preparation of mathematics teachers entails an undergraduate degree in mathematics, as in the case of Italy (Furinghetti 2000).

[32] Of course, it is possible to see both types represented in the same publication.

24.7.2 First Example

Burns (2010) examined how prospective secondary mathematics teachers at a small private university in the northeastern United States viewed the role of history of mathematics in the curriculum. The mixed methods study also included a brief description of key history of mathematics assignments pre-service that mathematics teachers were asked to complete as part of a secondary mathematics methods course. Post-administration of a five-question survey (when compared to pre-administration responses) indicated that they were more amenable to integrating history of mathematics in future teaching and felt more comfortable with their ability to incorporate history of mathematics.

Responses to the open-ended question, "What should the role of 'history of mathematics' play in the high school mathematics curriculum?" at the beginning of the study revealed that the majority of the prospective mathematics teachers in Burns' sample favored a minor or moderate role. Only three responses indicated a major role for history of mathematics in teaching. When the final questionnaire was administered, Burns found that the students felt more favorable, with only three students attaching a minor role to the history of mathematics. However, these results are somewhat problematic.

The secondary mathematics methods course provided "activities designed to enhance [participants'] exposure to the history of mathematics" (Burns 2010, p. 3), yet each activity described in the article focused on history as the "story of mathematics." For example, the prospective mathematics teachers in the course kept "track of mathematicians" and the mathematics they were famous for from their reading of *Fermat's Enigma* (Singh 1998), selected their "favorite mathematician" and created a short presentation about them, and finally, chose a unit within a high school mathematics course and described what history of mathematics content they would be able to incorporate into the unit. When the course activities are considered along with the pre-service mathematics teachers' responses indicating that they believed history of mathematics should have a major role in the high school curriculum, a contradiction arises. That is, if "history as story" (or, "history as anecdote")[33] is assessed as a minor way in which history is used in teaching mathematics, then the observation that "…basically I feel like history of mathematics should be 'sprinkled' on top of the lesson" (Burns 2010, p. 5) should not be coded as history having a major role in teaching.

Burns (2010) provided an example of research on exposing prospective teachers "to topics from history of mathematics and methods that could be used to teach these topics" (p. 2), but the exposure described lacked attention to strategies in which historical methods (e.g., mathematical procedures and techniques), historical problems, and primary sources are integrated when teaching mathematics. Indeed, she called attention to the need for more "to be done to develop a deeper understanding

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[33] Three modes of using history in teaching mathematics were given in Clark (2011): history as anecdote, history as biography, and history as interesting problems.

of [history of mathematics] before students get to a methods course" (p. 7), which is intimately connected to policy and standards that recommend history of mathematics courses for prospective secondary mathematics teachers.

24.7.3 Second Example

A similar intervention in a secondary mathematics methods course in Turkey was "designed to improve competencies regarding the integration of history of mathematics" in teaching mathematics courses (Gonulates 2008). The small intervention study involved 14 senior-level students over a 14-week period during the course. The intervention required the mathematics methods students to read assigned articles, which were chosen using the criteria of Gulikers and Blom (2001). Using the criteria, articles were selected if they fulfilled the aims of the study to portray the usefulness of historical materials when teaching mathematics, as well as the variety in which history of mathematics may be incorporated in teaching. The students were also required to participate on a class discussion board weekly by submitting a report that detailed their ideas about the weekly article and proposed use of history in teaching mathematics. Finally, "brainstorming and discussion" during the final week of the intervention enabled students to share their overall ideas about using history in teaching.

Two instruments were developed for the study, an attitude scale and a questionnaire. The attitude scale asked students to "state teaching strategies or instructional procedures that they [thought] they [could] use [history of mathematics] in [mathematics teaching]," and an accompanying questionnaire asked them to provide examples for each strategy (Gonulates 2008, p. 5). The results from the two instruments revealed that although the students' attitudes about integrating history of mathematics in teaching increased, the increase was not significant. Of greater interest, however, were results related to the extent to which the pre-service teachers were able to name ways in which they could integrate history of mathematics in teaching and the quality of the examples they identified. The pretest and posttest results for the total number of teaching strategies for incorporating history of mathematics were 55 and 73, respectively; the increase in the total number of examples for the strategies identified pre- and posttest was 53 and 69, respectively. Neither increase was significant. However, the increase in the quality of the examples as judged by three different juries was significant.

Gonulates' investigation raises several important issues for the field of history in mathematics education. The students' comments on the discussion board revealed that they held the belief "that the history of mathematics could be used more for motivational than for conceptual purposes" (2008, p. 9), which is a common theme for the investigations described in this section. The view that using history promotes mathematics (Furinghetti 1997) is a frequent outcome when "history as story" dominates pre-service teachers' experience with history of mathematics. Consequently, this view presupposes that the future practice of prospective teachers will entail using history to enrich their teaching in social, affective, and cultural ways, but will not be robust enough to aid in the learning of mathematical content. A potential solution to prompt the use of history of mathematics for the purpose of reflecting on mathematics (Furinghetti 1997) is to incorporate opportunities for prospective mathematics teachers in which they experience a quantifiable change in their own learning of mathematics through historical content, resources, and methods.

24.7.4 Third and Fourth Examples: Design of "History of Mathematics" Courses

Descriptive accounts for designing and implementing history of mathematics courses for prospective secondary mathematics teachers are abundant in the literature. Toumasis (1992) is an early example of proposing formal experiences in the history of mathematics in the training of secondary school mathematics teachers in Greece.

At the time, Toumasis observed that the content training of secondary mathematics teachers was "sound and supersufficient…, whereas the pedagogical training [was] quite inadequate" (1992, p. 289). Toumasis claimed that "teachers should be acquainted with the history of mathematics and mathematical ideas and its relation to science, and should acquire some familiarity with the way mathematicians work today" (p. 291). Furthermore, he claimed that prospective secondary mathematics teachers needed to receive training on "the role of the subject in history and the society" (p. 291), in addition to being taught mathematics content. Specific content of a course in the history or mathematics for prospective secondary mathematics teachers was not given; however, Toumasis outlined several tenets for teacher education programs, including a sample pre-service program structure and attention to such elements as providing students with opportunities to connect theory and practice.

Still other descriptions detail course content, required materials, and assignments for history of mathematics courses intended for prospective mathematics teachers, including Clark (2008) and Miller (2002). Miller designed and implemented a course that focused on the mathematics of five ancient cultures and which used two course texts on the history of mathematics from which to draw content and exercises. Miller's experience with teaching a history of mathematics course for the first time was the impetus for her "trial by fire" article; however, much of what she shared from her experience outlines many of the reasons why history of mathematics courses is not offered in teacher education programs.

Miller identified the lack of sufficient homework problems in any one text as a major obstacle in the implementation of the course. This, coupled with the realization that she was "not as prepared to teach the material" as she thought (2002, p. 339), made for a labor-intensive teaching experience. Furthermore, the curriculum committee at the State University of New York (SUNY) Potsdam established the mathematics course prerequisite at precalculus, thus potentially limiting the mathematical content and rigor of the course. The course was implemented at Miller's institution in anticipation of future NCATE accreditation to meet the program standard needs for prospective teachers to possess knowledge of the historical and cultural development of mathematics. Thus, developing foci for such a course, selecting appropriate materials and textbooks, identifying qualified and willing faculty, and setting the course prerequisite(s) may very well serve as the same obstacles for other institutional contexts.

24.7.5 History of Mathematics: Potential for Teachers' Mathematical Learning

Thus far there has not been explicit focus on why prospective teachers must know something of the history of mathematics, either for the development of their own knowledge or for learning concrete, innovative, or interesting ways to teach mathematics to pupils. Instead, the focus has been to summarize key activities that have taken place in the field regarding the existence of history of mathematics in mathematics teacher preparation. Perhaps the most essential aspect of the role of history of mathematics in mathematics education is what potential it holds for impacting the learning of the subject. In his text, *Elementary Mathematics from an Advanced Standpoint* (1908), Felix Klein wrote:

> …I shall draw attention, more than is usually done…to the *historical development of the science*, to the accomplishments of its great pioneers. I hope, by discussions of this sort, to further, as I like to say, your general *mathematical culture*: alongside of knowledge of details, as these are supplied by the special lectures, there should be a grasp of subject-matter and of historical relationship. (Klein 1908/1939 Pt. II, p. 2, emphasis in the original)

The importance of knowing and studying the accomplishments – in this case, mathematical accomplishments – as part of the (history of) mathematical education of prospective teachers has been valued and conjectured for over a century. It is vital to begin work on providing evidence in support of such conjectures.

24.7.6 First Example

Fulvia Furinghetti's work with prospective mathematics teachers in Italy provides important examples of how history of mathematics can be incorporated into teacher preparation programs with particular attention to "the conception of mathematics and its teaching…that students develop through their mathematics studies in university" (Furinghetti 2000, p. 43). As Furinghetti observed (and many would agree), university students with strong mathematical training become far removed from the mathematics they are required to teach and once arriving in the classroom their own teaching is similar to how they were taught mathematics in secondary school. In an effort to combat prospective mathematics teachers' falling back on old conceptions of teaching, Furinghetti asked her prospective teachers to "reflect on their mathematical knowledge, in particular on their beliefs about mathematics and its teaching" (p. 46). The activity used in the study focused on "definition," due to its critical role in learning mathematics.

The main component of the prospective teachers' work in the activity was to analyze definitions found at the beginning of old geometry books, including Italian translations of Euclid, Clairaut, and Legendre. Furinghetti (2000) outlined the outcome of the students' exploration of various geometric definitions (e.g., line, quadrilateral, square, trapezia), noting that "students became aware of the fact that definition has three different aspects" (p. 48) in that definitions must be logical, epistemological, and didactic (p. 49). Although the prospective teachers focused only on the didactic aspect of definitions, this in itself was an important mathematical orientation for the students and for this particular study. Here, the examination of various historical resources prompted prospective teachers to investigate questions about what is necessary, sufficient, and preferable information for a definition. In this way, the analyses in which the prospective teachers engaged were linked to proof, further strengthening their mathematical knowledge for teaching.

There are several important observations to make about this example of using historical content and resources with prospective teachers. It is important to note that they possessed strong mathematical backgrounds. However, insufficient research has been conducted on the mathematical background needed to study history of mathematics, particularly with respect to intentions for its use in mathematics teacher education and mathematics teaching.[34] However, it is significant that Furinghetti began the research with the goal that the prospective teachers would reflect on their mathematical knowledge. This difference sets Furinghetti's investigation apart from the research described in the first part of this section, most of which discussed outcomes primarily focused on the story of mathematics and learning to use history of mathematics as anecdote (Siu 1997). The important difference in the investigation Furinghetti conducted was how prospective teachers used history as

> a kind of 'magnifying glass' for the conceptual nodes of a certain theory, a means to identify critical points, to stop at the difficult concepts and to analyse them through the words of past authors. (Furinghetti 2000, p. 50)

24.7.7 *Second Example*

Prospective mathematics teachers' reflections are also the data source for Furinghetti (2007). In the experiment, 15 prospective secondary mathematics teachers were tasked with producing a sequence for teaching a particular concept in algebra for 9th and 10th grade students in Italy. The perspective from which Furinghetti designed the experiment was that the use of history of mathematics enables *reorientation*, that is, "that prospective mathematics teachers experience again the construction of mathematical objects" (p. 133). There were several phases in the experiment, including (1) analysis of the national mathematical programs from elementary school through the end of high school; (2) work with the history of mathematics to identify and study "the cognitive roots of algebra"; (3) design of the teaching sequence, applying both historical and theoretical perspectives from their course

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[34] Furinghetti noted that she served as the historian "guide" for students, providing "historical information…needed to interpret authors" (2000, p. 47).

work; and (4) discussion of the outcome of the teaching sequences produced, using both historical and classroom contexts to discuss how cognitive roots may emerge in the teaching sequence (Furinghetti 2007, pp. 135–136).

The prospective mathematics teachers' construction of teaching sequences for an algebraic concept produced a variety of artifacts. In addition to the planned sequences, the prospective teachers also produced exercises and problems for pupils and reports on implementation of excerpts from the teaching sequences. The significant finding of the study was the identification of the ways in which history of mathematics impacted these artifacts. Furinghetti (2007) identified two modes of impact: using history as a way of looking at the evolution of a particular concept and the reading of original sources. For each of these modes of impact, Furinghetti yet again provided empirical evidence for the power of history of mathematics to influence prospective mathematics teachers' mathematical knowledge. For example, for the "evolutionary" mode she observed that the prospective teachers held the idea that

> History provides meaningful examples of algorithms and methods that allow exploitationof the operational nature of mathematical objects;
>
> History suggests the development of the concepts in a visual/perceptual environment such as that provided by geometry. (Furinghetti 2007, p. 137)

Finally, it is important to again comment on the orientation from which Furinghetti conducted this experiment. As in the context with prospective mathematics teachers working on the notion of "definition" in mathematics, Furinghetti made it clear that guiding students in how to "do" history of mathematics was a primary concern. As part of her work with the 15 prospective teachers, she provided different types of sources and guidance on how to "look for information, to choose among different sources, to interpret original historical passages, to evaluate many elements, and to make their own choices" (p. 136). In this way, the varying background experiences of the participants were leveled out and this afforded opportunities for collaboration and discussion. Most importantly, "the participants were provided with motivation to learn some history of mathematics" (p. 141).

24.7.8 *Third Example*

Although history of mathematics received prominent attention in the 1997 new national curriculum in Norway, its role in mathematics teacher education did not receive similar attention. Smestad (2012) described the development and revision of a 6-h history of mathematics course he developed as part of a new course for prospective lower secondary mathematics teachers. Smestad established several goals for the students, all of which were focused on future pedagogical practices. The course:

> …should give the students examples of different ways of teaching with history of mathematics, it should be connected to the students' curriculum, it should give ideas that are suitable for different age levels in the 11–16 bracket, it should show how mathematics has…developed. (Smestad 2012, p. 1)

The students' evaluation of the first iteration of the course revealed that it was difficult for them to glean anything from the potpourri of topics. For the second iteration, Smestad focused entirely on the history of probability. Although Smestad provided a list of topics and a brief description of several examples from the course, of the outcome of the second iteration he stated only that "the mathematical learning was more obvious to the students" (2012, p. 3). Quantification of the extent of the mathematics learned and why it was more obvious to the students or what evidence supported either of these critical pieces of information are not known.

24.7.9 Fourth Example

Clark (2012) sought to qualify mathematical learning as a result of studying history of mathematics. In a history of mathematics course for prospective secondary mathematics teachers, students studied and used translations of primary sources as well as historical methods to solve problems connected to the mathematical content they would be responsible for in their future teaching. After studying the method of completing the square from al-Khwarizmi's famous text (ca. 825 CE), prospective teachers' journal reflections from four different semesters of the course were analyzed to identify key themes indicative of changes in their mathematical knowledge.

Excerpts from 80 of 93 student reflection journals provided insight into the ways in which the study of historical examples of solving quadratic equations using the method of completing the square revealed that the prospective teachers experienced two changes in their understanding of this mathematical idea. The prospective mathematics teachers came to understand the method of completing the square as a result of the geometric representation motivated by al-Khwarizmi's method. And they claimed that their previous experience with this mathematical topic was firmly situated in rote understanding of the quadratic formula emerging from the method of completing the square.

It was difficult to definitively identify whether the historical tasks, content, and historical sources were the primary influences of the changes in mathematical understanding experienced by the prospective mathematics teachers participating in the study. However, the reflections about the perspective on their own mathematical learning also influenced the prospective teachers' conceptions for how to incorporate history of mathematics in their future teaching. This prompts attention to Schubring's and his colleagues' (2000) concern that "…there is only scattered evidence about the effectiveness of the historical training in the later teaching practice" (p. 142) – and which continues to be of concern.

24.7.10 Summary

Each of the examples summarized in this section serves to remind the field that conducting research that details a clearer picture of what the role of history of mathematics in secondary mathematics teacher education is, and how teacher educators can best capitalize on what it offers to future educators, is difficult work. On the one hand, the extent to which the guidelines provided in MET1 – and now, MET2 – were or will be instituted in the United States remains unclear. Furthermore, the introduction of the Common Core State Standards Initiative in Mathematics (CCSSI-M) will have significant impact on mathematics teacher education. The newly created Mathematics Teacher Education Partnership (MTE-Partnership), a partnership of institutions of higher education, K-12 schools, school districts, and other stakeholder organization, has launched a collaborative effort to redesign secondary mathematics teacher education. The MTE-Partnership will identify best practices and guiding principles underlying such teacher education programs and the efforts of the partnership are intimately connected to CCSSI-M and common assessments that are attached to the Common Core State Standards. Finally, the extension of similar concerns and efforts applies to many, if not all, locations around the world, as the (largely unknown) outcomes of history of mathematics on mathematics teaching and learning will certainly influence its role in mathematics teacher education.

In order for teacher educators who advocate for the role of history of mathematics in mathematics teacher education to impart influence in the future, the broader field of mathematics education will demand evidence of positive impact of the integration of history of mathematics on pupils' learning of mathematics. The final section highlights several examples of interventions that have taken place in primary and secondary classrooms and which provide promise for imparting the influence needed in the future.

24.8 What Next: Teachers Using History of Mathematics in Teaching

This chapter was intended to provide an overview of the "state of the field" of history in mathematics education pertaining to the preparation of mathematics teachers. The previous sections described examples in the literature of the design and implementation of history of mathematics courses for prospective mathematics teachers, research on prospective teachers' attitudes towards learning history of mathematics, and teaching using historical perspectives, as well as qualitative research on how and what prospective teachers learn as a result of experiences with historical content. In addition to providing a representation of the field, suggestions of what is further needed to quantify responses to questions of why history of mathematics is necessary for the mathematical and pedagogical education of future mathematics teachers were offered. This final section offers a brief look at "what next?"; that is, after prospective teacher transition into classroom teaching, what are examples of efforts to incorporate the history of mathematics in teaching and what can be learned from them to further inform mathematics teacher education programs?

Table 24.4 displays a collection of six studies for which some element of history of mathematics was employed in a classroom intervention with pupils. The summaries

Table 24.4 Summary: recent examples of ways in which history of mathematics is used in classrooms

Author(s)	Age level, topic, and location	Intervention (including materials)	Methodology (data sources)	Outcomes and comments
Clark (2010)	46 pupils, grades 4 and 5 Contextual word problems involving multiplication, division, and conversion of units United States	Classroom teachers and school district mathematics specialists participated in professional development on an instructional unit created from two cuneiform tablets owned by Florida State University (FSU22 and FSU23). Pupils participated in an extended mathematics lesson using the materials, photos of FSU22 and FSU23, and local history	Qualitative; field notes, student work, teacher and mathematics specialists post-implementation survey	Classroom teachers participated with and observed their pupils' engagement with the instructional unit and reported increased student interest and attention. They also observed that pupils appeared to experience less difficulty with unfamiliar units (e.g., *eshe*, *bur*) and less anxiety with "word problems" that were situated in the ancient Babylonian context
Papadopoulos (2010)	20 pupils, grade 6 (two different Classroom environments: one computer lab, one paper-and-pencil classroom) Area of irregular shapes Greece	Inspired by the evolution of the Concept of area found in textbooks from the eighteenth to twentieth centuries, the author designed tasks and guided them to "reinvent" the methods for estimating the area of irregular shapes, for which they had no prior instruction	Qualitative; student work Artifacts from paper-and-pencil group and screen captures from computer lab group	The pupils applied Techniques that were the same as those given in the textbooks and some of the techniques developed by pupils were completely new
Ng (2006)	414 pupils in 8th year (177 in the experimental group; 237 in the control group) Relevant problems from ancient Chinese mathematical texts Singapore	Ancient Chinese Mathematics Enrichment Programme (ACMEP) entailed pupils' translating and solving problems taken from the *Nine Sections*. The intervention was 7 months in duration	Quasi-experimental (no random assignment: pupils selected which group they would be part of) assessments	Although there was an overall significant difference in academic achievement in mathematics between the experimental and control groups (favoring the experimental group), the difference could not be completely attributed to the ACMEP

Rowlands (2010)	36 gifted and talented pupils aged 14–15 and two groups of about 30 mixed ability pupils aged 16–17 Deductive geometry England	Pupils were introduced to the six levels of abstraction through the intervention containing two primary events	Qualitative; observations by one teacher and an academic, feedback questionnaires, formative assessment	Success of the pilot stage was judged primarily by the engagement of the learners
Thomaidis and Tzanakis (2007)	Two classes of 16-year-old students Ordering on the number line Greece	Pupils were taught according to the official syllabus and textbook for the first three chapters of the text. Regarding the fourth chapter, pupils were divided into two groups: those who had been taught “algorithmic” tools for solving quadratic inequalities (28 pupils) and those who had not (30 pupils)	Mixed methods; student responses to a three-item questionnaire, along with accompanying work	No significant difference was found between the post-“algorithmic” group and the pre-“algorithmic” group. Qualitative differences did point to the notion that some student difficulties paralleled the obstacles encountered in history regarding the conception of and ordering of negative numbers
Jankvist (2010)	Upper secondary pupils Public-key cryptography and RSA Denmark	A 67-page teaching module was prepared to introduce pupils to the historical case and the mathematics involved. Essay assignments were implemented in groups of three to five pupils	Qualitative; pre-implementation questionnaire involving historical, developmental, sociological, and philosophical questions and interviews conducted with a subset of the original group and five students from the 12 interviewees were interviewed during the module implementation	An existence proof for a module approach for history as a goal to occur with Danish upper secondary pupils

highlight the pupil age level and if appropriate, mathematical topic, what the intervention entailed, the methodology employed, and reported outcomes of the research.

The collection of studies highlighted here represents a broad range of pupil age levels, historical and mathematical content, and study design. What the analysis of the research revealed, however, is that most of the interventions were the result of ideas and research generated by scholars or mathematics teacher educators, not the result of classroom teachers who studied the history of mathematics (e.g., as a result of their pre-service mathematics preparation program) and then collaborated with others to conduct research of what occurred when using history in teaching. Finally, although progress is evident, questions and challenges regarding the role of history of mathematics in mathematics teacher education remain.

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Chapter 25
The Role of Mathematics in Liberal Arts Education

Judith V. Grabiner

25.1 Introduction

> World-famous golden-thighed Pythagoras
> Fingered upon a fiddle-stick or strings
> What a star sang and careless Muses heard
>
> –William Butler Yeats (1865–1939), "Among School Children"

Ireland's great poet beautifully reminds us how a legendary mathematician of antiquity not only discovered that musical harmony results when the lengths of vibrating strings are in the ratios of small whole numbers but also taught that the same mathematical harmonies produce the music of the heavenly spheres. Yeats expects his readers to know this history. The surrealist artist Salvador Dalí (1904–1989), in his painting "The Last Supper," places Jesus and his twelve disciples in part of a wooden dodecahedron, resembling the wooden model of this twelve-sided figure pictured in a famous drawing by Leonardo da Vinci (1492–1519). Plato in his *Timaeus* had said that the dodecahedron was the shape of the universe. Dalí's painting gains in power for those viewers who understand this symbolism.

Furthermore, not only ideas about numbers and shape but the very technical terms that underlie mathematics pervade Western culture from the "postulata" with which Thomas Malthus begins his "Essay on Population" of 1798 to the "algorithms" which humanists and scientists alike know are the basis for Internet search engines. Nor is this just in the Western tradition. Mathematics is found in virtually every human society, from ancient civilizations to contemporary cultures, both literate and nonliterate, all over the world. In Greece almost two and a half millennia ago, Plato wanted the rulers of his ideal Republic to study arithmetic, geometry, astronomy, and the mathematics of musical harmony, and those four subjects, along

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with grammar, rhetoric, and logic, made up the classical Seven Liberal Arts. In traditional Hindu architecture, numerical ratios are used to represent the mathematically determined structure of the universe. In classical India, not only was mathematics used to analyze poetic meter, mathematical results themselves were expressed in poetic form. In premodern China, mathematical writings were part of the canon of literary texts studied for the examinations to enter the civil service. At present, most universities in the United States require all students, whether these students aspire to be artists, social workers, or technologists, to take courses in mathematics. Mathematics, then, has played and still plays a central role in liberal arts education.

Yet mathematics is too often taught, and too often thought to be, a series of formulas, or a set of arbitrary rules for solving contrived and irrelevant word problems. It often acts as an instrument to keep less proficient students from entering certain fields. And though mathematics classes are often justified as helping teach students to think, or to think abstractly, much actual mathematics instruction teaches neither of these, instead producing frustration and a fear so pronounced that it has been given its own name, “mathematics anxiety” (Ashcraft 2002; Tobias 1993; Zaslavsky 1994). People who are otherwise well educated say, when confronted with the quantitative statements so pervasive in modern life, “Oh, I’ve always been bad at math.”

The present essay has four goals. First, it will briefly sketch the history of the continuous inclusion of mathematics in liberal education in the West, from ancient times up through the modern period; the focus on the West stems from the continuing influence of the idea reflected in the words of the title assigned to the author for this essay: “liberal arts education.” Second, it will elaborate on the brief remarks in this introduction to delineate the central role mathematics has played throughout the history of Western civilization, demonstrating that mathematics is not just a tool for science and technology (though of course it is that) but continually illuminates, interacts with, and sometimes challenges fields like art, music, literature, and philosophy – subjects now universally considered to be liberal arts.[1] Third, it will

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[1] In modern discourse about education, the term “liberal arts” has been defined and characterized in a variety of ways. It is of course built into the history of Western education. The influential Carnegie Foundation for the Advancement of Teaching has provided a list of contemporary “liberal arts” that goes beyond the traditional Western canon: English language and literature, foreign languages, letters, liberal and general studies, life sciences, mathematics, physical sciences, psychology, social sciences, visual and performing arts, area and ethnic studies, multi- and interdisciplinary studies, philosophy, and religion (Carnegie 1994, p. xx; Ferrall 2011, p. 9). In antiquity, as the next sections of this paper will describe, the list came to have seven items: arithmetic, geometry, astronomy, and music theory (the quadrivium), and grammar, rhetoric, and logic (the trivium) (Stahl 1977; Wagner 1983b). Those who compile such lists characterize liberal arts education as study undertaken for its own sake, as opposed to vocational education. As for the purpose of liberal arts education, it has been described as educating a free person, or as liberating the mind to pursue the truth, or as producing a cultivated person who can be both a good citizen and a leader of society. Liberal arts instruction has sometimes focused on the canonical texts of Western civilization as ways to build and reinforce the shared values of society. But such instruction has also been championed as suitable for the education of free individuals to be citizens in a democracy by developing the capacities for independent and critical thinking, logical analysis, effective communication, an understanding of the interrelations between different fields of learning, and imagination (Ferrall 2011; Kimball 1995; Nussbaum 2010; Sinaiko 1998). The present chapter recognizes and appreciates these

add a more global perspective to the contemporary liberal arts story, by showing how the mathematics present in many cultures – an important part of global history – can enhance the teaching of modern mathematics. Fourth, it will address some ways that mathematics teaching could take the subject out of the toolbox and bring it back to the university, replace frustration with appreciation and understanding, and reestablish mathematics as a liberal art.

25.2 Mathematics and Liberal Education in Western History

25.2.1 The Ancient World

The tradition of liberal arts education in the West goes back to antiquity. A liberal arts education was intended not to prepare one for a vocation or to accomplish some practical goal but to educate a free human being and citizen – though what “free human being” and “citizen” meant has changed over the years. And mathematics virtually always was counted among the liberal arts (Jaeger 1944; Marrou 1956).

In the Greek-speaking world, even before Plato’s time, mathematics was entwined with philosophy. A new attitude toward mathematics and science, detaching them from the practical or the metaphysical, is often dated from the time of Thales of Miletus (late sixth century BCE), who is said to have proved some basic geometric results and to have begun the Greek practice of understanding nature in terms of fundamental rational principles. To the pre-Socratic question “what is the basic unifying principle of the universe?” Thales answered that “all was water.” Then, Anaximander answered that all was the unbounded, Anaximenes that all was air, and Democritus that all was made of atoms. The Pythagoreans answered the question by teaching that “all is number.” Proclus (fifth century CE) credits Pythagoras himself with having transformed the study of mathematics into “a scheme of liberal education, surveying its principles from the highest downwards and investigating its theorems in an immaterial and intellectual manner”; this transformation, initiated by the Pythagorean school, was well established by the fifth century BCE.[2] The subdivision of mathematics into the four canonical sciences of arithmetic, geometry, astronomy, and music goes back at least to the prominent Pythagorean Archytas of Tarentum (early fourth century BCE) (Huffman 2011; Fauvel and Gray 1987, p. 57).

Plato himself in Book VII of his *Republic* gave mathematics a central role in the education of the rulers of his ideal state, who were to be philosophers as well as

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disparate views. The Carnegie list is useful to illustrate the types of subjects that constitute a liberal arts education today, and the present essay shares the view that modern liberal education’s most important goal is to educate independent and thoughtful citizens.

[2] For Proclus, see Proclus (1970, p. 53). The term “mathematics” itself reveals a liberal arts origin; the Greek root “mathema” was first more general, connoting merely “something learned,” and the “mathematikoi” were the inner initiates of the Pythagorean school. For pre-Euclidean logically structured geometry, see Knorr (1975, esp. p. 7) and McKirahan (1992, pp. 16–18).

kings. Plato acknowledged that mathematics is useful, but the needs of shopkeepers and generals are not why it is important. It is because the objects of mathematics are unchanging and eternal that their study is at the heart of liberal education. The study of mathematics, Plato said, compels the soul to look upward, drawing it from the changing to the real, from the uncertain to the certain, and from the world of illusion toward the truth (Plato, *Republic*, Book VII, 521c, 525d-529c; Plato 1961, pp. 575–844). Thus, mathematics is a "liberal" subject for Plato and his followers. Plato's outline for the education of the philosopher-rulers begins with arithmetic, followed by geometry, followed by astronomy, and is capped by the study of harmony. Astronomy goes beyond the study of the visible heavenly bodies to their pure mathematical shapes and motions, and harmony goes beyond physical music to the mathematical proportions involved (Plato, *Republic*, Book VII, 524e-531c; Plato 1961, pp. 575–844). Moreover, Plato often explained his philosophy using mathematical examples, most famously in the parable of the Divided Line, a geometric metaphor encompassing all of reality, from shadows to the Form of the Good (Plato, *Republic*, Book VI, 510d-513e; Plato 1961, pp. 575–844).

Aristotle, like Plato, distinguished learning for its own sake from more practical activities, and, also like Plato, put mathematics in the former category. Once there were people with leisure, said Aristotle, "those of the sciences which are directed neither to pleasure nor to the necessities of life were discovered" (Aristotle, *Metaphysics* 981b20-24; Aristotle 1941, pp. 689–926). Aristotle classified studies as theoretical, where the goal is knowledge; productive, where the goal is a product; and practical, where the goal is action. For him, mathematics, physics, and metaphysics are the theoretical sciences, and his theory of demonstrative science is illustrated by, and modeled on, the logically structured "elements of geometry" that existed before Euclid's definitive books drove out all previous competitors (Heath 1949, pp. 1, 5; McKirahan 1992, pp. 16–18). For Aristotle, the objects of mathematics are abstractions from sense experience (Aristotle, *De anima* 431b13-19; Aristotle 1941, pp. 535–603; Heath 1949, p. 65), a characterization that underlines the theoretical status of the subject. Aristotle also appreciated the aesthetic qualities of mathematics, saying "The chief forms of beauty are order and symmetry and definiteness, which the mathematical sciences demonstrate in a special degree" (Aristotle, *Metaphysics* 1078a37-b2; Aristotle 1941, pp. 689–926). Thus, for Aristotle as for Plato, mathematics shares goals and other characteristics with the liberal arts.

There were of course other subjects in Greek education, notably rhetoric, philosophy, and politics. Indeed, rhetoric, as championed by the Sophists such as Hippias of Elis (fifth century BCE), though criticized by Plato as the art of making the worse argument appear the stronger, was an important topic throughout antiquity. But the Sophists did not neglect mathematics. In fact Werner Jaeger credits the Sophists, beginning with Hippias, with having "altered the history of the world" by introducing mathematical instruction to their students, changing it from a subject of scientific research to a valuable part of education, with its value being the cultivation of the intellect (Jaeger 1944, vol. I, pp. 313–315). There was no unanimity on this point; the influential Greek orator and teacher Isocrates (436–338 BC) emphasized rhetoric and philosophy in his highly influential program of instruction, which, in the Hellenistic age, was often preferred to that of Plato and which was emphasized in the more literary and rhetorical educational ideal adopted by the Romans (Jaeger 1944, vol. 3, pp. 46–47; Kimball 1995, p. 19; Marrou 1956, pp. 119–120).

Education in the Roman period generally emphasized politics and rhetoric. Still, even the champion of oratorical instruction Quintilian (40–118 CE) conceded that mathematics sharpens the intellect and teaches how to construct an argument (Grant 1999a, p. 99). The Greek term "Enkuklios paidaea" that described higher education in antiquity was always taken to include mathematics, and the Latin phrase "artes liberales" was seen as similar to "enkuklios paidaea" (Kimball 1995, p. 21; Marrou 1956, pp. 243–245; Morrison 1983, p. 32). "Liber" – free – meant the arts of the mind of the free individual as opposed to the mechanical arts.

The influential orator Cicero held that to be truly human, one needed to have been "perfected in the arts appropriate to humanity" (Cicero, *De re publica* I.xvii.28), and, although mathematics was not foremost in his educational agenda, he included it on the list of "artes liberales" essential to the liberal education of a gentleman (Cicero, *De oratore* III.xxxii.127; Grant 1999a, p. 100). Cicero also reported that Plato became convinced of a country's intellectual nature by seeing that it had produced geometrical drawings, rather than just by observing that its land was cultivated (Cicero, *De re publica* I.xvii.29).

Throughout the Graeco-Roman period, then, mathematics remained part of education. Of course, sometimes the mathematics taught did not go very deep. Still, at least lip service was paid to its role, and even lip service keeps a tradition alive and capable of fuller resurrection.

25.2.2 The Middle Ages

The idea of the liberal arts continued into the medieval period. The Latin encyclopedists of the fifth through seventh centuries hoped to preserve the intellectual heritage of classical learning. They combined the intellectual traditions of Neoplatonism with Christianity and linked these with the handbook tradition of popular culture. The encyclopedists needed an organizing principle for all these topics, and the principle chosen was the concept of the liberal arts, a principle that continued to organize knowledge into the twelfth-century Renaissance and beyond.

Martianus Capella's fifth-century *Marriage of Philology and Mercury* is the first work to fully present the Seven Liberal Arts (Stahl 1977, pp. 21–39). Martianus's Seven Liberal Arts, described allegorically as seven bridesmaids, were grammar, rhetoric, logic, arithmetic, geometry, astronomy, and harmony or music. Martianus explicitly ruled out medicine and architecture, classifying them as "mundane matters," that is, professional pursuits, not liberal ones, pursued for their own sake (Stahl 1977, vol. 1, p. 93). Sometimes in medieval teaching, logic was assimilated into rhetoric, and often the mathematics was superficial, but Martianus's classification ensured that mathematics would remain part of the "arts of free people" (Stahl 1977; Wagner 1983a).

Although the Christian Roman Emperor Justinian closed the pagan philosophical schools, including Plato's Academy in Athens, in 529 CE, the Greek version of the liberal arts did not die. The early Church fathers had been interested. Clement of Alexandria (150–215 CE) was willing to include the liberal arts as a first stage in education that ultimately led to philosophy and Christian wisdom (Grant 1999a, p. 101), while Augustine (354–430 CE), much influenced by Neoplatonism, saw the liberal arts as pathways to the divine order underlying creation, especially, he said, "in music, in geometry, in the movements of the stars, in the fixed ratios of numbers" (Grant 1999a, p. 101). Cassiodorus (c. 480–c. 575 CE) also included the liberal arts in Christian education. In sixth-century Spain, Isidore of Seville wrote that mathematics is a legitimate and important component of Christian culture, supporting his view with a text from the *Apocrypha*: "Not in vain was it said in the praise of God: You made everything in measure, in number, and in weight" (*Wisdom of Solomon* XI, 20; Høyrup 1994, pp. 177–178).

In the monasteries, monks copied and preserved both Greek and Latin manuscripts. Beginning in the eighth century, notably under Alcuin of York, cathedral schools taught both the trivium and quadrivium. For the quadrivium, texts included arithmetic based on the work of Nicomachus of Gerasa, the first four books of Euclid's *Elements of Geometry* as adapted and abridged by Boethius, some astronomy based on an abridgement of Ptolemy's *Almagest*, and various Greek materials on music. Mathematics was needed in this period to determine the calendar in general, and the date of Easter in particular, and of course to solve various practical problems, but otherwise there was little interest in further research. Still, as a beginning of medieval education, the cathedral schools were important in preserving the role of mathematics, and Pope Sylvester II (999–1003) even began to introduce the Hindu-Arabic number system, as well as basic geometry and astronomy, in the cathedral school at Rheims (Katz 2009, pp. 325–327).

The twelfth century marked the high point of the Seven Liberal Arts in medieval education. Hugh of St. Victor, best known as the writer of an influential educational handbook for theology students, stressed the Seven Liberal Arts as appropriate for the liberated mind, calling them "the best instruments…for the mind's complete knowledge of philosophic truth" (Grant 1999a, p. 103). The celebrated cathedral school in Chartres, France, was marked by a Platonic orientation, and its chancellor, Thierry of Chartres, argued that the study of mathematics led directly to the knowledge of God (Grant 1999a, p. 104; McInerny 1983, pp. 254–255).

Yet though these educators knew that there was a great ancient tradition in mathematics, they did not know much about its substance. This situation changed with the flowering of translation activity in the twelfth century that has become known as the Twelfth-Century Renaissance (Haskins 1927). Europeans came to know about Greek works, mostly in their Arabic versions as studied in the Islamic world, through travel, contacts in southern Italy, and the European reconquest of parts of Spain. Because of the prestige of mathematics in the liberal arts tradition and also because of the importance of mathematics and astronomy and astrology for social and religious needs, major translators like Gerard of Cremona and Adelard of Bath assiduously searched for the principal works of men like Ptolemy and Euclid to translate from Arabic into Latin.

By the end of the twelfth century, major works of Greek mathematics and astronomy in their entirety, most of Aristotle's philosophy, and the books on algebra and arithmetic of Muḥammad ibn Mūsā al-Khwārizmī were all available in Latin. In the thirteenth century and beyond, with the rise of medieval universities, scholars worked to assimilate the expanded ancient traditions into medieval Christian culture. Aristotle in particular presented a sophisticated approach to philosophy and a range of subjects, from biology to metaphysics, that did not fit the old patterns. The new materials needed to be integrated with the old liberal arts as well as with Christian thought and practice.

Still, though the educational ideal may no longer have been the study of liberal arts for their own sake (McInerny 1983, pp. 248–9), many medieval thinkers from the thirteenth century on continued to value the traditional liberal arts, including mathematics, at least as stepping-stones to a religiously meaningful life. Thomas Aquinas (1225–1274) explicitly recognized the Seven Liberal Arts in general and mathematics in particular as "paths preparing the mind for the other philosophical disciplines," although he equally explicitly said that they were by no means sufficient for the Christian studying philosophy (Kimball, pp. 66–67; McInerny 1983, p. 251). Men like Roger Bacon (1214–1294) advocated mathematical instruction, saying that without mathematics "nothing of supreme moment can be known" in any other science – a more applied kind of mathematics, perhaps, but still seen as essential for learning (Grant 1999b, p. 199; Masi 1983, p. 151). Research in fields like geometrical optics, infinite series, and the graphing of variable magnitudes was undertaken in the fourteenth century by men like Robert Grosseteste, Richard Swineshead, and Bishop Nicole Oresme (Katz 2009, pp. 324–363).

However distinguished medieval mathematical research was, though, scholars of the Renaissance self-consciously reached back beyond it in their enthusiasm to revive the glories of the ancient mathematical traditions.

25.2.3 The Renaissance and After

The glories Renaissance thinkers saw themselves reviving included Plato as well as Aristotle and also included considerably more mathematics. Especially striking in light of what we now call the liberal arts is the use of geometry in perspective in painting, with men like Piero della Francesca, Leonardo da Vinci, and Albrecht Dürer highly proficient in both geometry and art (Field 1997). Also striking is the new mathematization of music, again based on supposed Greek models (Fauvel et al. 2003). And the ideal of the Renaissance man, competent in many areas of knowledge, foreshadows the modern idea of a well-rounded student with a general liberal education. In urban and court culture, liberal education was occasionally extended also to women (Cruz 1999, pp. 250, 252; Grendler 1989, pp. 93–102; Schiebinger 1989, p. 12).

One influential Renaissance educational theorist, Pier Paolo Vergerio, wrote a treatise in 1404 that emphasized the importance of liberal studies, encompassing history, moral philosophy, poetry, but also the traditional Seven Liberal Arts

(Cruz 1999, p. 243). Later on as artists became more prestigious, drawing and thus a bit of geometry became more important liberal subjects. What came to be called humanist education was linked both to Christian piety and to civic values and public service. It is true that Renaissance mathematical teaching was at first quite practical and carried out in the so-called abacus schools, but for many aristocrats such teaching was too closely associated with business and trade and too marked by rules of thumb. So in courts and in the households of the social elite, men of the stature of Luca Pacioli and Mauricio Commandino taught more theoretical mathematics, and courtly patrons of humanists included mathematicians at their courts as well (Rose 1975, p. 293). Influential humanist teachers like Vittorino da Feltre (1378–1446) of Mantua regarded mathematics as a crucial component of humanistic education, and he even included some women among his students (Cruz 1999, p. 251; Rose 1975, p. 16).

University mathematics teaching in Renaissance Italy used texts like Euclid, Sacrobosco's *Sphere*, Ptolemy's *Almagest*, and the Alphonsine astronomical tables (Marr 2011, pp. 62–64). And as the humanist curriculum expanded from Italy into France, England, and Germany, mathematics came with it (Cruz 1999, p. 249). In Germany, Philipp Melanchthon in the 1520s gave special emphasis to the place of mathematics and astronomy in the university curriculum (Cruz 1999, p. 240; Westman 1975, p. 170). Johann Sturm (1507–1589) in Strasbourg also went beyond grammar and rhetoric and Biblical texts in having his students study mathematics and science (Cruz 1999, p. 249).

Humanism was not the only impetus to expanding the teaching of liberal arts. There was a Catholic response to these new trends. In the mid-sixteenth century, the Jesuits begin to conduct schools, teaching not only grammar, philosophy, and theology but also mathematics, geography, history, and astronomy, often using original texts. Jesuit schools grew in number, importance, and influence; by 1600 there were 236 Jesuit colleges, some outside of Europe, and by 1750 there were 669 Jesuit colleges and 24 universities;[3] the Jesuits number Descartes, Voltaire, and Condorcet among their influential pupils. Mary Ward (1585–1645) established a network of humanist schools for girls patterned on the Jesuit model; by 1631 there were many such schools and hundreds of pupils, who were taught mathematics as well as Latin and Greek (Cruz 1999, pp. 252–253). Thus, the sixteenth century produced an educated elite, people who communicated and were grounded in a cultural heritage that transcended the boundaries of language, of gender, of region, and even the distinction between Protestant and Catholic. The liberal arts continued to be thought of as providing intellectual discipline, as well as teaching moral examples and civic duty.

Humanism's deep interest in rediscovering, translating, and circulating ancient Greek texts reinvigorated mathematics with new sophisticated sources. Indeed, Francesco Maurolico (1494–1575) spoke explicitly of a "renaissance of mathematics." This "renaissance" brought advanced mathematical texts – Archimedes, Pappus, Apollonius, and Diophantus – into European mathematics and also included a drive to restore parts of the text which had not survived (Rose 1975, p. 179). Such

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[3] See Chapple (1993a, p. 7), Cesareo (1993, p. 17), Cruz (1999, p. 250), and Taton (1964).

attempts at restoration themselves became real mathematical research, like Descartes' and Fermat's reconstruction of works of Apollonius using modern algebraic methods, and, not so incidentally, developing analytic geometry. A similar example is found in Fermat's notes on Diophantus's *Arithmetica*, notes that jump-started modern number theory, including the conjecture now called Fermat's Last Theorem (Katz 2009, pp. 498–499; Rose 1975, p. 292). The mathematical Renaissance was embodied in universities, especially in Italy, and what was taught in those universities helped initiate the great achievements of mathematics and science in the seventeenth century (Grendler 2002, pp. 408–429).

In the seventeenth century, mathematics proved overwhelmingly successful in modeling the laws of the cosmos. The Newtonian idea that natural laws were the laws of God linked mathematics to Christianity. The new authority of mathematics led to its institutionalization in university education, as part of the intellectual heritage of any liberally educated man. And the success of what was billed as the new scientific method strengthened the philosophical and political ideas associated with the Enlightenment.

The eighteenth and nineteenth centuries saw an even greater role for mathematics as useful in warfare and statecraft but also as intellectual enrichment and discipline. Women as well as men participated in the latter category. The journal "Ladies' Diary," from 1704 to 1841, was dedicated to teaching women the mathematical sciences and contained problems and puzzles which were successfully solved by female readers (Schiebinger 1989, p. 41). Mathematics as intellectual enrichment and discipline is seen across the board in educational institutions as different as the universities designed to provide a gentleman's education like Oxford; Harvard and other early American colleges; Cambridge University, which since the late eighteenth century was dominated by the mathematical Tripos examination; and the German universities dedicated to pure research, together with their American followers like Johns Hopkins and the University of Chicago (Merz 1904, pp. 89–301; Rudolph 1962, pp. 244–286, 349–354). The liberal arts ideal in the colleges in the Colonial period of the United States helped inspire the founding of many small American colleges throughout the eighteenth and nineteenth centuries (Rudolph 1962, pp. 44–67).

Columbia College in 1919 pioneered requiring all freshmen to take a course called "Introduction to Contemporary Civilization in the West" based on the liberal arts. In the 1920s with the Progressive movement in America, colleges addressed anew the question of what a liberal arts college ought to be. Influential responses included Alexander Meiklejohn's "Experimental College" at the University of Wisconsin, which began with the study of Plato; the complete Great Books curriculum founded in the 1930s and still in force at St. John's College in Maryland; and the explicit classicism of Robert Maynard Hutchins and Mortimer Adler who in the 1930s began the Core Curriculum at the University of Chicago. With the advent of the Cold War between the United States and the Soviet Union, liberal arts education was promoted as developing the free and inquiring intellect in opposition to totalitarianism; this view was influentially expressed in the book *General Education in a Free Society: Report of the Harvard Committee* (1945). All these and their many followers explicitly intended to revive the ancient liberal arts tradition in twentieth-century society (Rudolph 1962).

As a result of all these trends, the ideal of general or liberal education, in opposition both to premature specialization and to vocationalism, continues to structure most university-level education in the United States today. The category "liberal arts colleges," listing hundreds of such schools, appears in almost all guidebooks to American higher education; for instance, the *U. S. News and World Report* list gives data on 266 such schools. Colleges of this type are being developed on the American model in other countries as well, including New York University in Abu Dhabi; Xing Wei College in Shanghai, China; Bard College's partner institutions in St. Petersburg, Russia, and in Berlin; Yale University in Singapore; and Smith Women's College in Malaysia. Quest University in British Columbia is Canada's first private liberal arts institution. And mathematics remains part of such liberal arts education.

As for pre-university education, teaching mathematics is almost universal. Although the prevalence of mathematical instruction may be in some part due to mathematics' place in the traditional liberal arts curriculum, many other justifications for its inclusion are given in the modern world: preparing students for the vastly increasing number of modern technical careers, helping students understand science and economics, aiding citizenship, and expanding and training the mind to take on any intellectual challenge.

Rarely, though, is teaching mathematics justified by saying that mathematics is and has always been at the heart of the disciplines we now identify as the liberal arts. Furthermore, in the past, "liberal arts" always designated an education for an elite. The study of the liberal arts in general, and mathematics as a liberal art in particular, was never extended to an entire citizenry. To educate modern citizens for a free society, though, this essay will argue that it is necessary to go beyond teaching mathematics solely as the prerequisite to something else.

Elsewhere the author has sketched the history of the central role mathematics has played in Western thought (Grabiner 1988, 2010). The reasons for that central role go far beyond simply following the pattern of traditional education. As will be shown in the next sections, that central role has been the result of two aspects of mathematics. One is that mathematics appears to provide truths, truths that can be proved. The other is that mathematical ideas work to produce knowledge of the world, in areas ranging from the arts to the study of nature. Philosophers of mathematics often call these aspects of mathematics "certainty" and "applicability." Historically, these aspects of mathematics have often been invoked as slogans by those advocating including mathematics in education. But the history goes far beyond slogans. Together, these two aspects of mathematics – certainty and applicability – explain and illuminate both how and why mathematics has been central throughout the history of the liberal arts. Demonstrating that central role throughout history justifies making mathematics a key part of liberal education in the world today. To see mathematics in this central role, we will look first at mathematics as a provider and exemplar of truth.

25.3 Mathematics, Truth, and Proof

25.3.1 The Greek Model

As in all of Western thought, one must begin with Plato and Aristotle. Plato said that the certainty of mathematics comes from the perfection of its subject matter. In the natural world, everything changes, comes into being, and passes away; the objects of mathematics, by contrast, are unchanging and eternal. Mathematics provides a model for Plato's philosophy of ideal Forms that transcend our changing experience: the idea of justice, the ideal state, and the idea of the Good. In the Western tradition, the common terms "certain" and "true" preserve Plato's belief in an unchanging transcendent reality, and Plato consistently argued for it using examples from mathematics. And, as discussed earlier, Plato decreed that the philosopher-ruler of his ideal *Republic* should study mathematics to be brought to the truth.

For Aristotle, though, the truth of mathematics comes more from its method than from its subject matter, since the results of mathematics can be demonstrated logically, proceeding from self-evident assumptions and clear definitions. Aristotle held that other subjects could also gain certainty if they could be put into the same form, the form of what he called a demonstrative science (Heath 1925, pp. 117–121; McKirahan 1992). Thus mathematics, especially Euclid's geometry, came to be seen as a model for much of scientific and philosophical reasoning. For instance, medieval theologians tried to demonstrate the existence of God from first principles. In 1675, Benedict Spinoza wrote an *Ethics Demonstrated in Geometrical Order* (Spinoza 1953), with explicitly labeled axioms and definitions, and including theorems like "God or substance consisting of infinite attributes … necessarily exists," whose proof he closes with the letters QED. Isaac Newton's great *Mathematical Principles of Natural Philosophy* of 1687 has the same definition-axiom-proof structure. Newton called his famous three laws of motion "axioms," and he labeled and proved the fundamental laws of his mechanics as theorems (Newton 1934).

The American *Declaration of Independence* is another example of an argument whose authors tried to inspire faith in its certainty by using the Euclidean form. "We hold these truths to be self-evident," the mathematically sophisticated author, Thomas Jefferson, began his argument, "that all men are created equal" (Becker 1922; Cohen 1995). Another self-evident truth in the *Declaration* is that if any government fails to secure human rights, it is the right of the people to alter or abolish it. The second section of the *Declaration* makes clear that this is a proof: it says that King George's government does not live up to the postulates, followed by the words "to *prove* this, let facts be submitted to a candid world" (Italics added). And the actual declaration of American independence is in fact the conclusion of an argument, so it begins with a "therefore": "We, *therefore* … declare, that these United Colonies are, and of right ought to be, free and independent states" (Italics added).

The same model of reasoning also pervades the law, and its mathematical antecedents are sometimes explicitly recognized. For instance, Christopher Columbus

Langdell, the pioneer of the case method in American legal education and Dean of Harvard Law School in the 1870s, was part of a long tradition that saw law as a science very much like geometry (Hoeflich 1986; Kalman 1986, p. 3; Seligman 1978). Law, according to Langdell, is governed by a consistent set of general principles. One gets these principles by looking at individual cases by induction, according to Langdell, in a manner reminiscent of Newton's *Principia.*[4] But once one has the general principles, one proceeds as in geometry. The correct legal rules are to be logically deduced from those general principles and then applied to produce the correct legal ruling in line with the facts of a particular case (LaPiana 1994, p. 3; Seligman 1978, p. 36). In the theory of law as in liberal arts like philosophy and the study of nature, the Euclidean model of reasoning has shaped conceptions of proof, truth, and certainty.

25.3.2 Symbols and Algorithms

The ability of mathematics to exemplify truth was not limited to geometry. Between the Renaissance and the eighteenth century, the paradigm governing mathematical research changed from a geometric one focused on proof to an algebraic and symbolic one. In algebra just as in Aristotle's view of demonstrative sciences like geometry, one can consider the method independently of the particular subject matter. The algebraic or algorithmic method in mathematics finds truths by manipulating symbols according to fixed rules. The algorithmic approach long preceded symbolic algebra, entering Europe in the Middle Ages.

Influential in developing the idea of "algorithm" was the twelfth-century Latin translation of a work on the Hindu-Arabic number system by the ninth-century mathematician Muḥammad ibn Mūsā al-Khwārizmī. This system is the base-10 place-value system now universally learned in school, and the new computational power it produced was enormous. Multiplication is relatively easy in a place-value system, since multiplying by 3 million is as simple as multiplying by 3. The rules for producing new truths involving these numbers, including rules not only for ordinary arithmetic but also for more intricate problems like taking square roots, were called the "method of al-Khwārizmī." Later his name became Latinized into Algorismus and then, perhaps by association with "arithmos" for number, into "Algorithmus," whence the modern term "algorithm" for any set of powerful rules that can be easily and mechanically applied. The algorithms used to calculate with the Hindu-Arabic numbers are now known to every schoolchild. Equally important, these algorithms were eventually seen as similar to the later manipulations of symbolic algebra.

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[4] Distinguishing experimental philosophy from reasoning from arbitrary hypotheses, Newton wrote, "In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction" (Newton 1934, p. 547). Once Newton had his general principles, his *Principia* could take the logical structure familiar from Euclid's *Elements*.

The Arabic word “algebra,” derived from the Arabic title of another book by al-Khwārizmī, *Kitāb al-jabr wa l-muqābala*,[5] the first Arabic-language treatise on algebra, at first designated the systematic study of the processes of solving equations, with the equations expressed in words. But the word “algebra” today first brings algebraic symbolism to mind. In the 1590s, François Viète systematically developed and exploited general symbolic notation much like that used currently (Klein 1968; Struik 1969, pp. 74–81). This now familiar invention has the power to produce abstract, general truths in mathematics. For instance, given any pair of distinct numbers, say, *7* and *9*, schoolchildren are taught that not only does $7+9=16$, so does $9+7$. There are of course infinitely many such examples. Viète’s general symbolic notation for the first time allows the writing down of the infinite number of such facts all at once:

$$B+C=C+B.$$

A century later, Isaac Newton summed up the power and generality of Viète’s innovation by calling algebra “universal arithmetic.” Newton meant that we could derive and prove general algebraic truths from the universal validity of the symbolic manipulations that obey the laws of ordinary arithmetic.

More can be learned from a less trivial example than adding two numbers. First consider the quadratic equation

$$2x^2-11x+14=0.$$

Imagine being told, “*2* and *3 ½* are the solutions.” But being given these solutions provides no information about how those answers were obtained. However, with general symbolic notation, it is clear that *every* quadratic equation has the form

$$ax^2+bx+c=0,$$

where a is any nonzero real number and b and c can be any real numbers.

Solving the *general* equation by the algebraic technique of completing the square gives the general solution, the well-known quadratic formula:

$$x=\left[-b\pm\sqrt{\left(b^2-4ac\right)}\right]/2a.$$

Unlike the numbers *2* and *3 ½* in the original example, numbers which could have been produced by many possible arithmetic operations, each term in the general solution reveals the way it was produced; for instance, the term ac was

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[5] Khwārizmī’s title can be translated as “the book of restoring and balancing,” where the Arabic “al-jabr” or “restoring” was interpreted as adding the same thing to both sides of an equation and “al-muqabala” or “balancing” the subtraction of the same quantity from both sides of an equation (Berggren 1986, p. 7). The sense of “al-jabr” as “restoring” remains in Spanish, where, for instance, in *Don Quixote*, Part II, Chap. XV, a bonesetter is an “*algebrista*” (Merzbach and Boyer 2011, p. 207).

produced by multiplying the coefficients a and c. Thus, the general solution to the quadratic equation preserves the record of every operation performed on the coefficients to find that solution. In the original example, $a = 2$, $b = -11$, $c = 14$, so it is now apparent how the answers *2* and *3 ½* were obtained from the coefficients in the equation. More important, the process of finding the solutions by completing the square proves in general that these and only these are the solutions.

Recognizing the generality and problem-solving power of symbolic algebra, in the 1630s René Descartes and Pierre de Fermat, working independently, combined the method of geometry and proof with the method of symbolic algebra into a new subject, analytic geometry. Problems in geometry, Descartes said, could be solved by translating geometric relationships into algebraic expressions, manipulating the algebraic expressions according to the rules of algebra, and translating the results of these manipulations back into the geometric solution of the original problem. He and Fermat, using the insight that problems could be translated back and forth between algebra and geometry, solved a range of previously intractable problems, and Fermat, in his geometric work, anticipated some of the discoveries of the calculus (Boyer 1956; Mahoney 1973).

Furthermore, Descartes' success in devising a new method for solving problems that had stumped the ancient Greek geometers helped him conclude that "method" was the key to all progress. When he theorized about this in his *Discourse on Method*, though, he drew on the structure of Euclidean geometry as well as that of algebra. He argued that the method of making discoveries begins with analyzing the whole into the correct "elements" from which truths could later be deduced. "The first rule," he wrote in the *Discourse*, "was never to accept anything as true unless I recognized it to be evidently such."

The second rule "was to divide each of the difficulties which I encountered into as many parts as possible, and as might be required for an easier solution…." Then, "the third rule was to [start] … with the things which were simplest and build up gradually toward more complex knowledge" (Descartes 1637a, Part II, p. 12). A mathematical example, from Descartes' *La Géometrie* (Descartes 1637b), is building up a polynomial from a set of linear factors, making visible the truth that a polynomial equation has as many roots as the polynomial's highest degree. Descartes' rules in the *Discourse* mirror his "rules of reasoning in philosophy" and are part of a long tradition of arguing by means of analysis and synthesis (Gaukroger 1995, pp. 114, 124–126, 180). But later thinkers took Descartes himself as a starting point, considering him "the figure who stands at the beginning of modern philosophy" (Gaukroger 1995, p. vii), and his influence on subsequent philosophy, from Locke's empiricism to Sartre's existentialism, has been enormous. For the purposes of this essay, the key point is the large debt Descartes' philosophical views about method owe to his ideas about mathematics.

Later on in the seventeenth century, Gottfried Wilhelm Leibniz was so inspired by the power of algebraic notation to simultaneously make and prove mathematical discoveries that he invented an analogous notation for his new differential calculus. Leibniz's dy/dx and $\int y dx$ notation is still prized and used because of its heuristic power. In fact what Leibniz meant by choosing the term "calculus" was that he had invented a set of algorithms for operating with the differential operator *d* (Leibniz 1969). Furthermore, Leibniz envisioned an even more general symbolic language that would be able to establish the indisputable truth in all areas of human thought. Once there was such a symbolism, which Leibniz called a "universal characteristic," he predicted that if two people were to disagree, one could say to the other, "let us calculate, sir!" and the disagreement would be resolved (Leibniz 1951). These ideas of Leibniz make him a pioneer in what has become the modern philosophical discipline of symbolic logic.

Other seventeenth-century thinkers also pointed out the algorithmic and mechanical nature of thought. For instance, Thomas Hobbes wrote, "Words are wise men's counters, they do but reckon by them" (Hobbes 1939, Chap. 4, p. 143). By the eighteenth century, not only did many mathematicians think that discovery and proof should be based on abstract symbolic reasoning but prized such reasoning above intuition and geometry. For instance, in 1788 Joseph-Louis Lagrange wrote his *Analytical Mechanics* with no diagrams whatsoever. Other scientists inspired by this ideal introduced analogous heuristically powerful notations in their own fields. For instance, Antoine Lavoisier and Claude-Louis Berthollet developed a new chemical notation that Lavoisier called a "chemical algebra" (Gillispie 1960, p. 245). Anyone who has ever balanced a chemical equation has benefited from their innovation.

The success of these ideas about symbolism, both within and beyond mathematics, led the Marquis de Condorcet to write that algebra "contains within it the principles of a universal instrument, applicable to all combinations of ideas" and to go so far as to say that the general algebraic method could "make the progress of every subject embraced by human intelligence… as sure as that of mathematics" (Condorcet 1793, p. 238; pp. 278–279). He used these ideas to support his central thesis that "the progress of the mathematical and physical sciences reveals an immense horizon … a revolution in the destinies of the human race" (Condorcet 1793, p. 237). Here his view epitomizes the Enlightenment idea of progress in its clearest form. In the nineteenth century, George Boole produced the first modern system of symbolic logic and used it to analyze a wide variety of complicated arguments (Boole 1854). His system, developed further, underlies the logic used by digital computers today, including applications ranging from automated theorem-proving to translators, grammar checkers, and search engines, approaching a full embodiment of Condorcet's dream of the algebraic method embracing every subject.

25.3.3 The Method of Analysis

The second rule in Descartes' *Discourse on Method*, the idea of divide and conquer, fits beautifully with the Greek atomic theory, which had just been revived in the seventeenth century. If all matter is made up of small particles, one could analyze the properties of the whole on the basis of the properties of the parts. This idea became central to both chemistry and physics, and indeed still is. Familiarity with these ideas also permeates art and literature, in examples as different as the nineteenth-century pointillism of Georges Seurat and the conclusion of the poem "Mock on, mock on, Voltaire, Rousseau" by William Blake (1757–1827):

> The Atoms of Democritus
> And Newton's Particles of Light
> Are sands upon the Red Sea shore,
> Where Israel's tents do shine so bright.

Another line of influence of Descartes' divide-and-conquer method can be seen in economics, notably in Adam Smith's 1776 *Wealth of Nations.* Smith analyzed the competitive success of economic systems by using the concept of division of labor. He explained how the separate elements of the economy, with each one acting as efficiently as possible, combine to produce the economic system's overall prosperity. Famously, Smith said that each individual in the economy, while consciously pursuing only his individual advantage, is "led as if by an Invisible Hand to promote ends which were not part of his original intention" (Smith 1974, p. 271), the optimal outcome for the entire society.

In France after the Revolution came another application of the divide-and-conquer method, inspired directly by Smith's views. Gaspard François de Prony had the job of calculating a set of logarithmic and trigonometric tables. He undertook to do this by applying Smith's idea about the division of labor. Prony described a hierarchical divide-and-conquer system to produce the tables. First, mathematicians decide which functions to use; then, technicians reduce the job of calculating the functions to a set of simple additions and subtractions of preassigned numbers; and finally, a large number of low-level human "calculators" carry out the actual additions and subtractions.

In England, Charles Babbage took Prony's analysis of large-scale mathematical calculation and embodied it in a machine, the first digital computer ever conceived (Hyman 1982). Babbage described the basic idea in a chapter elegantly called "On the Division of Mental Labour" (Babbage 1832, Chap. XIX). Mathematicians were to decide what the machine would do and with what numbers it would do it, and then a machine could carry out the low-level task of performing the additions and subtractions. Babbage was a follower of Leibniz's views on the power of notation to make mathematical calculation mechanical. So, the first modern computer owes much both to the analytical method that Descartes promoted and to Leibniz's ideas about algorithms.

25.4 Mathematics Versus Skepticism

The fact that there is a subject, mathematics, which seems to be able to find irrefutable truth, has been philosophically powerful in other ways than those so far described. Since the existence of mathematics supports the conclusion that some sort of knowledge truly exists, the success of mathematics has long been used as a weapon against skepticism. For instance, Plato, going beyond his teacher Socrates' critical method, used mathematical examples repeatedly to show that learning and knowledge were possible. In the 1780s, Immanuel Kant used the example of Euclidean geometry to show that there could indeed be non-tautological knowledge that is independent of sense experience and thus argued that metaphysics, skeptics like David Hume to the contrary, is also possible (Kant 1950; Kant 1961). This same point – that mathematics is knowledge, so that objective truth does exist – is convincingly conveyed when Winston Smith, the protagonist in George Orwell's novel *1984*, heroically asserts, in the face of the totalitarian state's overwhelming power over the human intellect, that two and two are four.[6]

Another way that mathematics, as an example of certain knowledge, has challenged skepticism is by providing an answer to what has been called the problem of the criterion (Popkin 1979). If all sides to a controversy seem to disagree, what is the criterion by which the true answer can be recognized? Of course, if there were only one system of thought available, people might well accept it as true, a situation somewhat like the status of Roman Catholicism in the Middle Ages. But the Reformation presented alternative religious systems, the Renaissance revived the thought of pagan antiquity, and Cartesianism and the new science of the seventeenth century provided further challenges. Now finding a criterion that could identify the true system seemed urgent. But mathematics seemed to have solved this problem.

What, then, asked philosophers, was the sign of the certainty of the conclusions of mathematics? The fact that nobody disputed them. So the criterion of truth, many seventeenth- and eighteenth-century thinkers concluded, was universal agreement. Voltaire elegantly summed up this conclusion when he wrote, "There are no sects in geometry. One does not speak of a Euclidean, an Archimedean" (Voltaire 1901a, c). What every reasonable person agrees upon, that is the truth. Applying this to religion, Voltaire observed that some religions forbid eating beef, some forbid eating pork; therefore, since they disagree, they both are wrong. But, he continued, all religions agree that one should worship God and be just; that must therefore be true. Applying the same idea to ethics, Voltaire said, "There is but one morality… as there is but one geometry" (Voltaire 1901a, b).

25.5 Mathematics and Its Applications

But mathematics is more than an exemplar of truth and certainty; it also works in the world, not only the world of engineers and bankers but the world of the liberal arts as well. But why should mathematics apply to the world at all? For Plato, it is because this world is an approximation to the higher mathematical reality. For Aristotle, on the other hand, mathematical objects are abstracted from the physical world by the intellect. Later empiricists, such as John Stuart Mill, have agreed with Aristotle. However, since mathematical ideas often are applied to situations

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[6] The point will be clearer with a fuller quotation: "With the feeling…that he was setting forth an important axiom, he wrote: *Freedom is the freedom to say that two plus two make four. If that is granted, all else follows"* (Orwell 1949, p. 81; his italics).

quite different from those in which they arose, the empiricist answer seems insufficient. In any case, Plato's answer has wielded great influence.

25.5.1 Mathematics and Nature

From the ancient Pythagoreans onward, many thinkers have looked for the mathematical reality beyond the appearances. In the sixteenth and seventeenth centuries, Copernicus, Kepler, Galileo, and Newton looked for that mathematical reality – and found it in the laws that govern the physics of motion and the behavior of bodies in the solar system. The Newtonian world-system that completed the Copernican revolution was embodied in a mathematical model, based on the laws of motion and inverse-square gravitation, and set in Platonically absolute space and time (Cohen 1980, pp. 63–67; Newton 1934, pp. 6–9). The success of Newton's physics not only strongly reinforced the view that mathematics was the right language for science but also strongly reinforced the emerging ideas of progress and of truth based on universal agreement.

These successes engendered important theological and philosophical implications. The mathematical perfection of the solar system could not have come about by chance, argued Newton. The cause of this perfection had to be an intelligent designer, God, who chose to create the universe in a pattern so well suited to humanity. The search for other examples of design and adaptation in nature inspired considerable research in natural history, especially on adaptation, and this research was an essential prerequisite to Darwin's discovery of a nontheological explanation for this adaptation: evolution by natural selection.

25.5.2 Mathematics and the Arts

Other examples of the uses of mathematics come from the arts. The mathematical theories that underlie music began with the Pythagoreans and have continued since, revived and expanded upon beginning in the Renaissance. The modern study of pitch, intensity of sound, meter, and the psychology and physiology of hearing, to say nothing of the technologies of musical reproduction, all have a sophisticated mathematical basis.[7]

The same is true of the visual arts. In the Renaissance, stimulated by the rediscovery of Euclid's geometrical work on optics, painters used geometry to give the viewer the visual sense of three dimensions. Several Renaissance artists did original work in geometry, notably Piero della Francesca (1410–1492) and Albrecht Dürer (1471–1528). Piero's *De prospectiva pingendi*, the first mathematical treatise on

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[7] (Fauvel et al. 2003; Field 2003; Helmholtz 1954; Karp 1983; Jeans 1956; Newman 1956, pp. 2278–2309 Wardhaugh 2009; Wollenberg 2003)

perspective for painting, showed geometrically how to depict objects in three dimensions, viewed from a particular standpoint, on the picture plane. Dürer's *Underweysung der Messung* of 1525, the first geometric text written in German, included applications of geometry to constructing regular polygons and polyhedra, to architecture, and to typography, and Dürer was the first to show how to project three-dimensional curves onto two perpendicular planes. The work of these artist-mathematicians helped direct attention to many of the key ideas of what, in the seventeenth-century work of Girard Desargues and Blaise Pascal, became the new mathematical subject of projective geometry (Field 1997; Kemp 1990).

25.5.3 Optimization

An especially striking example of mathematical applicability, which links mathematics with science, philosophy, and theology, is given by the history of optimization. The use of optimal principles to explain the world goes back at least to the first century CE when Heron of Alexandria showed that the law of equal-angle reflection of light minimizes the distance the light travels. In the seventeenth century, Fermat showed that Snell's law of the refraction of light minimized what Fermat called the light's "path" (distance times resistance), which, since he assumed that velocity varies inversely with resistance, is mathematically equivalent to saying that light follows the path that minimizes its time of travel (Mahoney 1973, p. 65, pp. 382–390).

Leibniz, using his newly discovered calculus, produced algorithms for finding maxima and minima and applied them to elegantly re-derive Fermat's result (Leibniz 1969; Struik 1969, pp. 278–279). In his philosophy, Leibniz argued that the universe itself is constructed by God according to optimal principles. For Leibniz, a possible world is one consistent with the laws of logic; those possible worlds with more different beings in them are better than the others, and our world is the best of all possible worlds because it is the one in which the total of existing things is maximized (Lovejoy 1936, pp. 50, 144–146, 173).

In the eighteenth century, Colin Maclaurin, when aged sixteen, used the calculus, and some theological assumptions about eternal life, to argue that the Christian doctrine of salvation maximizes the future happiness of good men (Maclaurin 1714; Tweddle 2008). This argument applied the same methods many mathematicians used to apply the principle of least action in physics, as well as to design the most efficient windmills and waterwheels. Maclaurin's classmate at Glasgow, the philosopher Francis Hutcheson, used the same idea of mathematical optimization to demonstrate his laws of virtue. For instance, Hutcheson wrote in 1728, "That Action is best, which procures the greatest Happiness for the greatest Numbers" (Hutcheson 2004, Sect. III, p. 177). Later on, a similar approach is found in the utilitarianism of Jeremy Bentham, embodied in the famous phrase "the greatest good for the greatest number."

This line of reasoning recalls the ideas of Adam Smith, who had been a student of Hutcheson's at Glasgow. In words resembling Hutcheson's, Smith influentially wrote, “Upon equal…profits…every individual naturally inclines to employ his capital in the manner in which it is likely to afford the greatest support to domestic industry, and to give revenue and employment to the greatest number of people of his own country” (Smith 1974, Book IV, Chap. II). From Smith’s work, a set of ideas common not only to mathematics but also to philosophy and theology has entered the vocabulary of the most hardheaded of economists.

25.5.4 The Social Sciences

Just as the example of mathematical truth made finding truth elsewhere seem possible, so the examples of applying mathematics to natural science inspired those seeking to perfect other disciplines. This was especially true for the early nineteenth-century pioneers of the social sciences, Auguste Comte and Adolphe Quetelet. Both men knew their science, Comte having been influenced principally by Lagrange, Quetelet by Pierre-Simon Laplace. Lagrange’s *Analytical Mechanics* of 1788 had claimed to reduce all of mechanics to mathematics. Comte went further: if physics was built on mathematics, so was chemistry built on physics, biology on chemistry, psychology on biology, and finally his own new creation, *sociology* (a term Comte coined) would be built on psychology (Comte 1830, Chap. 11).

Comte said that science had once been theological, invoking God, then metaphysical, invoking general philosophical principles, but now science, including social science, would be based only on observed connections between things, a stage of science he called “positive,” stimulating the beginning of the philosophical stance called positivism. Comte’s philosophy, owing much to mathematical physics, influenced not only twentieth-century logical positivism but also the views on science and history held by Ludwig Feuerbach (1804–1872) and Karl Marx.

Still, Comte did not develop a quantitative social science. Here the prime mover was Quetelet, for whom the applicability of mathematics was crucial. “We can judge of the perfection to which a science has come,” he wrote in 1828, “by the ease with which it can be approached by calculation” (Quetelet 1828, p. 233). Quetelet was especially impressed by Laplace’s use of the normal curve of errors to determine planetary orbits from observations. Quetelet found empirically that not only the distribution of measurement errors but also the distribution of many human traits, including height and chest circumference, gave rise to the same normal curve. From this, he defined the statistical concept and the term, “average man” *(homme moyen)* (Porter 1986, p. 52). These ideas are essential to modern social science.

25.5.5 Freedom and Determinism

Quetelet observed also that many social statistics, such as the number of suicides in Belgium, produced roughly the same figures every year. One might think that crimes are the result of free individual choice. But the constancy of these rates over time, he argued, suggests that murder or suicide has constant social causes. Quetelet's discovery of the constancy of crime rates raised an important philosophical question: Is human behavior determined by social laws, as he seemed to think, or are we free to choose our fate?

Laplace, even though he needed probability to do physics, did not believe that the laws governing the universe were ultimately statistical. Since the true causes are not yet known, Laplace said, people believe that events in the universe depend on chance. But in fact everything is determined. To an intelligence which knew all the forces in nature and the exact situation of the beings that composed it, said Laplace, "nothing would be uncertain" (Laplace 1951, Chap. II).

Later in the nineteenth century, though, the mathematical physicist James Clerk Maxwell, in his work on the statistical mechanics of gases, argued that statistical regularities in the large reveal nothing at all about the behavior of any individual. Maxwell cared about this point because it allowed for free will. Maxwell considered such issues not just because of physics but because he had read and pondered the work of Quetelet on the application of statistical thinking to society (Porter 1986, pp. 118–119). A similar dispute about the meaning of probabilistically stated laws has arisen in modern debates over the foundations of quantum mechanics.

So, discussions of basic philosophical and theological questions like "is the universe an accident or a divine design?" for Newton and Leibniz, "is there free will or are we all programmed?" for Quetelet and Maxwell, or "are the laws of nature ultimately statistical?" for Laplace, Maxwell, Bohr, and Einstein owe much to questions about the applicability of mathematics to the world and to society.

25.6 When "Mathematics as Universal Truth" Fails

So far, although the people discussed have disagreed about philosophical matters, they have not argued about the essential truth of mathematics itself. However, universal agreement about mathematics and its relationship to the natural and social worlds did not survive the nineteenth century, and the older ideas of universal mathematical truth and the consequent universal agreement have had an interesting trajectory since then. To sketch this trajectory, one must ask what happened to the rest of thought when the very nature of mathematics and its relationship to the world seemed to change. The place to begin is with the overturning of the long-held view that there is only one geometry.

25.6.1 Questioning Euclidean Geometry

Since the time of Euclid, mathematicians had viewed his Fifth Postulate as considerably less self-evident than the others. Although Euclid's postulate is sometimes called the “Parallel Postulate,” it does not mention parallel lines at all. Instead of the more intuitive postulate “Only one parallel to a given line can be drawn through an outside point” that one finds in many high-school texts today, Euclid’s Fifth Postulate was this assumption: “That, if a straight line falling on two straight lines makes the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, meet on that side on which are the angles less than the two right angles” (Euclid, *Elements* 1925, Postulate 5; Heath 1925, p. 202).

Over many years since Euclid, mathematicians thought that the postulate should not be assumed but proved. When mathematicians tried to prove it from Euclid’s other postulates by indirect proof, they deduced a variety of surprising “absurd” consequences from denying Postulate 5. Among the consequences of denying the postulate are “parallel lines are not everywhere equidistant” and “there can be more than one parallel to a given line through an outside point.” In the early nineteenth century, Carl Friedrich Gauss, Janos Bolyai, and Nikolai Ivanovich Lobachevsky each separately recognized that these consequences were not absurd at all, but rather were valid results in a different, equally consistent geometry (Gray 1989, pp. 86–90, 106–124). Gauss chose an appropriate name for the new geometry: non-Euclidean (Bonola 1955, p. 67).

Kant had said that space (by which he meant the only space he knew, Newton’s three-dimensional Euclidean space) was the form of all our perceptions of objects, a unique intuition of the mind in which we must order these perceptions (Friedman 1992; Kant 1961). But what, then, can be said about non-Euclidean space? The nineteenth-century psychologist and physicist Hermann von Helmholtz asked whether Kant might be wrong. Could we imagine ordering our perceptions in a non-Euclidean space? Yes, Helmholtz said, if we consider the world as reflected in a convex mirror (Helmholtz 1962, pp. 240–241). The reader can do this by consulting M. C. Escher’s famous drawing “Hand with Reflecting Sphere” or by using a car’s side mirror that carries an explicit warning that the space we see in it is not Euclidean. In the convex mirror, parallel lines, defined by Euclid as lines on the same surface that do not meet, are no longer seen as equidistant.

Now the philosophy of mathematics as universal truth was under attack. Euclidean and non-Euclidean geometry give the first clear-cut historical example of two mutually contradictory mathematical systems, of which at most one can actually represent the world. This suggests that mathematical axioms are not self-evident truths related to the world at all, but may be, as Helmholtz argued, empirically based. Our idea of space is gained through sight and through touch. Two-dimensional beings living on a visibly curved surface, said Helmholtz, would invent a non-Euclidean geometry. So, Kant to the contrary, our idea of space is not unique, let alone necessarily Euclidean. To a non-empiricist, our ideas of space may even be intellectually free creations.

Inspired by Helmholtz’s philosophy of geometry, the English mathematician and philosopher William Kingdon Clifford (1845–1879) discussed the matter in the broadest possible historical and philosophical context. Clifford said, “It used to be that the aim of every scientific student of every subject was to bring his knowledge of that subject into a form as perfect as that which geometry had attained." But no more. "What Copernicus was to Ptolemy," Clifford wrote, "so was Lobachevsky to Euclid" (Clifford 1956, pp. 552–553). Before Copernicus, said Clifford, people thought they knew everything about the entire universe. Now, Clifford stated, we know that we know only one small piece of the universe. The situation is similar in geometry.

Before non-Euclidean geometry, the laws of space and motion implied an infinite space and infinite time, whose properties were always the same, so we knew what is infinitely far away just as well as we knew the geometry in this room. Lobachevsky has taken this away from us, said Clifford. That space is flat and continuous is true just as far as we can explore, and no farther. Speaking statistically about our experience of space, Clifford continued, "If the property of elementary flatness exists on the average, the deviations from it being too small for us to perceive, we would have exactly the conceptions of space that we have now" (Clifford 1956, p. 566). So Clifford, using non-Euclidean geometry, drew conclusions similar to those of the philosophers and scientists who concluded that the laws of nature were ultimately statistical. In fact, Clifford used his ideas to attack the entire Newtonian philosophy of science, especially singling out Newton's idea that human beings can have a universal theory of gravitation that applies to all bodies whatsoever.

Another perspective on these questions about geometry came from the great French mathematician, physicist, and philosopher of science Henri Poincaré (1854–1912), who disagreed both with Kant and with Helmholtz. If, as Helmholtz said, geometry were an empirical science, it would not be an exact science but would be subjected to continual revision. Poincaré of course knew about non-Euclidean geometry, so he knew that we have more than one space in our minds. From this he concluded that geometrical axioms are neither synthetic a priori intuitions (as Kant had said) nor experimental facts (as Helmholtz said). Geometrical axioms, said Poincaré, are conventions. So which set of axioms should be used in geometry? Poincaré said that, as long as we avoid contradictions, "our choice among all possible conventions may be guided by experience, but our choice remains free." The axioms of geometry are really only definitions in disguise. And Poincaré concluded, "What are we to think of the question: Is Euclidean geometry true? The question has no meaning. We might as well ask if the metric system is true, and the old weights and measures are false. One geometry cannot be more true than another; it can only be more convenient" (Poincaré 1952, p. 50). This very modern conclusion might shock Plato and Newton, but makes clear how revolutionary non-Euclidean geometry was for fields outside of mathematics.

The power of the Euclidean model, of course, did not die. Some influential thinkers stood by him. For instance, the famous English economist William Stanley Jevons (1835–1882) thought that Plato was right and Helmholtz was wrong. Transcendental or necessary truth, according to Jevons, is not produced by experience; it is recognized rather than learned (Richards 1988, pp. 87–90). The great English algebraist Arthur Cayley (1821–1895) was also not convinced by Helmholtz's argument that two-dimensional beings living on an obviously curved surface would invent a geometry describing such a curved surface. Cayley said that those beings would in fact invent three-dimensional Euclidean geometry. It would be, he said, “a true system” applied to “an ideal space, not the space of their experience” (Richards 1988, p. 90). And the Dutch philosopher J. P. N. Land thought that Helmholtz’s convex-mirror experiment proved nothing, saying in 1877 that the world in the mirror requires practice to interpret in a Euclidean way, but we can learn to do it (Richards 1988, pp. 100–101).

Nevertheless, Clifford’s views seemed to fit better with the increasingly empirical nature of nineteenth-century natural science. Popularizers of natural science like the physicist John Tyndall (1820–1893) and the Darwinian paleontologist Thomas Henry Huxley (1825–1895) insisted that people can only claim to know the information received through the senses. And transcendental realities, say Tyndall and Huxley, contrary to Plato and Kant, are both unknown and unknowable (Richards 1988, pp. 104–105). For Clifford and Helmholtz, this unknowability applied to space; for the agnostic Huxley, it applied to God.

The conclusions drawn from the existence of non-Euclidean geometries had a counterpart in nineteenth-century algebra. William Rowan Hamilton devised a noncommutative algebraic system, the quaternions, a system in which the product of two elements *ab* is not necessarily equal to the product *ba*. Discoveries like this led mathematicians increasingly to view their subject as a purely formal structure. Algebra was not the general science of number, any more than geometry was the science of space. Mathematics is nothing more than, as the American algebraist Benjamin Peirce put it in 1870, “the science that draws necessary conclusions” (Peirce 1881). The world is no longer, as Plato had thought, an imperfect model of the true mathematical reality. Instead, mathematics provides a set of different intellectual models, which can, but need not, apply to the one empirical reality. The sciences now merely model reality; they no longer claim to speak directly about it. Kurt Gödel applied this view to mathematics itself, using a formal model of mathematical reasoning to prove the surprising result that the consistency of mathematics cannot be demonstrated. Now a philosopher could say that there is no certainty anywhere, not even in mathematics (Barrett 1958, p. 206).

25.6.2 Space and the Social Sciences

Yet the widespread applicability of mathematics to the world meant that the new geometrical ideas would immediately become involved in still other debates, notably in the social sciences and the arts. As the example of Helmholtz indicates, one place where geometry has interacted with social science is in the psychology of perception. Even before the birth of non-Euclidean geometry, Bishop Berkeley and Thomas Reid had pointed out that we do not really see distance; we merely infer distance from the angles that we do see. Consider, for instance, looking upward at the corner in a rectangular room where the ceiling meets the walls. This is perceived as a place where three 90° angles come together. But if one measures the individual angles as they actually appear and are projected onto the viewer's retina, each of the angles is greater than 90° and together they add up to 360°. Our visual space is not the same as the space we claim we see.

And humans do not see parallel lines well either. Helmholtz did an experiment where he asked people in a dark room to put little points of light that got progressively farther away into two lines that always maintained the same distance from each other – that is, parallel lines. But the lines these people made out of these points of light turned out to curve away from the observer. Experiments like these have led psychologists to conclude that visual space is not represented by any consistent geometry (Wagner 2006).

Social scientists have also investigated the Kantian-influenced idea that spatial categories in language are direct projections of humanity's shared innate conceptual categories. As the cultural linguist Stephen Levinson has documented, the evidence suggests otherwise (Levinson 1996; Levinson 2003). In both language and concepts, people in different cultures have other ways of ordering their perceptions than in Euclidean space. For instance, particular directions may have special connotations, and "closeness" can be cultural as well as metrical. Further, some cultures, Levinson reports, use the idea of a fixed coordinate system, having four cardinal directions and referring locations to those, as one does in saying, "the house is north of the tree." But other cultures' concepts are more like Leibniz's idea of space in which there is no absolute space, just the relations between objects, including the observer. This is what one does in saying, "the house is to the left of the tree." No coordinate system is needed. One's perceptions can also be organized by letting the intrinsic properties of an object define the spatial location, as when one says, "The house is on the mossy side of the tree." Some cultures strongly emphasize only one of these methods of ordering objects in space, while others use a variety of these methods (Levinson 1996, pp. 140–145; Levinson 2003, pp. 31–39). There is no universal agreement here.

In modern society, directions can be given by saying, "Go north for five miles, then turn east for two miles," but also by saying, "Keep going straight until you get to the traffic light, and then turn right until you reach the supermarket." The second method, the way GPS systems give directions, follows Leibniz's relational view of space. In fact, GPS navigational systems are changing people's supposedly innate and universal intuitions of space. A Maryland cabdriver who recently bought a GPS told the author, "I used to have the whole geography of greater Baltimore in my head. I don't any more. I think about each trip as, drive to such-and-such exit, then make two right terms, one left turn. And when I leave you off, to get back to the expressway I'll just reverse that – one right turn, then two left turns. I will get back, but I won't know where I've been." Kant's view of Euclidean space as the unique form of all possible perceptions common to all human minds is subject to challenge from psychology and linguistics as well as from philosophy.

25.6.3 Space, Philosophy, and Art

Using both non-Euclidean geometry and relativity, the Spanish thinker José Ortega y Gasset (1883–1955) drew revolutionary cultural and political conclusions in order to refute what he called the “dogmatisms” of absolutism, provincialism, utopianism, and rationalism (Ortega 1968; Williams 1968, pp. 148–157). All absolutisms are wrong, said Ortega, whether in geometry, physics, or philosophy; reality, he said, is relative. Provincialism incorrectly assumes that our own experience or values are universal. Like Clifford, Ortega said that Euclidean geometry was provincial, an unwarranted extrapolation of what was locally observed to the whole universe. Instead, argued Ortega, reality organizes itself to be visible from all viewpoints, and Einstein’s theory of relativity, which requires new geometries of space-time, promotes the harmonious multiplicity of all possible points of view. Thus, all cultures have valid points of view. There is a Chinese perspective, Ortega said, that is “fully as justified as the Western” (Williams 1968, p. 152).

The last two of Ortega’s dogmatisms, utopianism and rationalism, are linked and again are both wrong. Since the Greeks, Ortega said, reason has tried to build an idealized world and say, this is true, this is how it is. Before relativity theory, Hendrik Lorentz (1853–1928) had said that matter must get smaller as it goes faster; that is, said Ortega, matter yields so that the old laws of physics can continue to hold. But Einstein said instead, “Space yields. Geometry must yield, space itself must curve.” According to Ortega, Lorentz might say, “nations may perish, but we will keep our principles,” but Einstein would reply, “We must look for such principles as will preserve nations, because that is what principles are for” (Williams 1968, p. 155).

In another example of radical thinking facilitated by new views of geometry, the surrealist theorist Gaston Bachelard wrote an essay attacking both reason and logic. Bachelard advocated restoring reason to its true function, which is not to shore up the agreed-upon order; instead, as the new geometries show, reason is “a turbulent aggression” (Henderson 1983, p. 346). The Russian thinker P. D. Ouspensky not only attacked the limitations of three-dimensional space, which he identified with Euclidean geometry, but also declared, “A is both A and not-A,” and “*Everything* is both A and not-A” (Henderson 1983, p. 253), an explicit repudiation of Aristotle and of all deductive logic. More recently, the French cultural theorist Jean Baudrillard applied these ideas about geometry to refute what was left of the eighteenth-century idea of progress, writing, “In the Euclidean space of history, the fastest route from one point to another is a straight line, the one of Progress and Democracy. This, however, only pertains to the linear space of the Enlightenment. In our non-Euclidean space of the end of the twentieth century, a malevolent curvature invincibly reroutes all trajectories” (Baudrillard 1994).

Modern artists and theorists of art alike were excited by the idea of new geometries. Artists often equated non-Euclidean geometry with the fourth dimension, since both seemed to attack the conventional Euclidean norms. The revolutionary role of the new geometries in art was aided by writers both from literature and psychology. For instance, in 1884 Edwin Abbott wrote a book popularizing the fourth dimension called *Flatland* (Abbott 1953; Abbott 2010). In the country of Flatland, everybody lives on a two-dimensional plane. Abbott's two-dimensional beings are visited by a sphere, which comes from the third dimension. But the Flatlanders cannot conceive of the sphere. They interpret the sphere's intersections with the plane as merely a succession of circles. The problem the Flatlanders have in imagining the third dimension, according to Abbott, is the same as the problem that we three-dimensional creatures have in understanding the fourth dimension. The psychologist of perception Gustav Fechner said that we could think of 2-dimensional creatures as shadows of 3-dimensional figures. In the same way, then, said Fechner, our world is a 3-dimensional "shadow" of the fourth-dimensional reality (Henderson 1983, p. 18). Even Euclidean ideas like Abbott's about the fourth dimension owed a debt to non-Euclidean geometry, since non-Euclidean geometry prepared the way for conceiving alternative kinds of space.

Henri Poincaré's view, discussed earlier, about freedom of choice in geometry was also very attractive to a number of artists (Henderson 1983, p. 55). The key point for the modern artist, after all, was a new freedom from the tyranny of established laws. Thus, Tristan Tzara, the founder of the art movement called "Dada," spoke of "the precise clash of parallel lines." If this should sound like a contradiction, Tzara counseled against worry; the artist can transcend contradictions. The French critic Maurice Princet challenged artists to reverse the prejudices of Renaissance perspective (Henderson 1983, p. 68). Instead of portraying objects on a canvas as "deformed by perspective," they should be expressed "as a type." In Renaissance perspective art, a rectangular table would appear on the canvas shaped like a trapezoid. But a rectangular table should not look like a trapezoid. It should be straightened out into a true rectangle. Likewise, the oval of a glass should become a perfect circle. This describes what is done in many masterpieces of Cubist art.

In Euclidean geometry, when something is moved, it keeps its shape and size. But theorists of Cubism, like Jean Metzinger and Albert Gleizes, declared that Riemann's geometry gives painters the freedom to deform objects in space. Similar views can be found embodied in architecture. For instance, Zaha Hadid, the first woman to win the Pritzker Architecture Prize, constructs buildings that express such ideas. She wrote of her work, "The most important thing is motion, the flux of things, a non-Euclidean geometry in which nothing repeats itself, a new order of space" (Hadid 2008). In the work of artists like these, non-Euclidean geometry has reshaped both our artistic and our intellectual landscapes.

All of these theorists and artists were saying that, beyond the Euclidean world that conventional people think they inhabit, there is a higher reality, a reality that artists alone can intuit and reveal. Non-Euclidean geometry both liberated and legitimated these new approaches to art. The American mathematician Morris Kline has observed, "Non-Euclidean geometry knocked geometry off its pedestal, but also set it free to roam" (Kline 1953, p. 431). And the freedom that geometers claimed for themselves was subsequently bequeathed to many people who may have thought of themselves far from mathematics but well within the traditional liberal arts. The freedom of geometry reinforced a wealth of other social and historical forces in remaking modern culture.

25.7 Anti-Mathematics as a Historical Force

Opposition to the supposed primacy of mathematics in human thought has also influenced the liberal arts and reveals negative perceptions about mathematics that educators neglect to their peril. Some of this opposition is not hostile to all of mathematics, just to its extension beyond its legitimate sphere. For instance, an early opponent of what Ortega later called "provincialism" was, perhaps surprisingly, Isaac Newton. Men like Descartes and Leibniz seemed to Newton to be saying that self-evident assumptions alone sufficed to figure out how the universe works. Newton disagreed. According to Newton, there are many mathematical systems God could have used to set up the world. One cannot decide a priori which is correct, Newton said, but must observe and experiment to find which laws actually hold. Although mathematics is the means used to discover the laws, God set up the world by free choice, not mathematical necessity. This is how Newton justified concluding that the order we find in nature proves that God exists (Newton 1934, p. 544).

Also in the seventeenth century, Blaise Pascal, who made major contributions to mathematics and, with Fermat, was a coinventor of probability theory, contrasted the "esprit géometrique" (abstract and precise thought) with what he called the "esprit de finesse" (intuition) (Pascal 1931, *Pensée* 2), holding that each had its proper sphere but that mathematics had no business outside its own realm. "The heart has its reasons," wrote Pascal famously, "which reason does not know" (Pascal 1931, *Pensée* 277).

In the eighteenth century, Thomas Malthus, in his *Essay on Population*, accepted the Euclidean deductive model. Indeed he began his essay with two "postulata": man requires food, and the level of human sexuality remains constant (Malthus 1798, Chap. 1). His consequent analysis of the way population growth will outstrip food supply rests on mathematical models. But his goal was to discredit the predictions by Condorcet and others of continued human progress modeled on the progress of mathematics and science, as Malthus's mathematical models predict eventual misery and vice instead.

In a nineteenth-century example, the mathematical reductionism of men like Lagrange and Comte was opposed by a great mathematician, Augustin-Louis Cauchy. Cauchy wrote in 1821, "Let us assiduously cultivate the mathematical sciences, but let us not imagine that one can attack history with formulas, nor give for sanction to morality theorems of algebra or integral calculus" (Cauchy 1892, p. vii; Cauchy 2009, p. 3). More recently, computer scientist Joseph Weizenbaum attacked the modern, computer-influenced view that human beings are nothing but processors of symbolic information, arguing that the computer scientist should "teach the limitations of his tools as well as their power" (Weizenbaum 1976, p. 277).

All the examples so far granted some legitimacy to mathematical argument. But there also have been people who have no use at all for the method of analysis, the mathematization of nature, or the application of mathematical thought to human affairs. For instance, the Romantic movement in the nineteenth century championed the organic view of nature over the reductionist mechanical explanations they attributed to Descartes and Newton.[8] The Romantic view is epitomized by a stanza from William Wordsworth's poem *The Tables Turned:*

> Sweet is the lore which Nature brings;
> Our meddling intellect
> Mis-shapes the beauteous forms of things:
> We murder to dissect.

Reacting against Quetelet-style statistical thinking on behalf of the dignity of the individual, Charles Dickens in his 1854 novel *Hard Times* satirized a son who betrays his father and then defends himself by saying that in any given population a certain percentage will become traitors, so no blame should be attached. And Dickens has his hero, Stephen Blackpool, denounce the analytically based efficiency of the industrial division of labor, saying it regards workers as though they were nothing but "figures in a sum" (Dickens 1854, Book II, Chap. V).

Although the certainty of mathematics, and thus its authority, has sometimes been an ally of liberalism, as it was for Voltaire, Jefferson, and Condorcet, the Russian novelist Evgeny Zamyatin saw how mathematics could also be used as a way of establishing an unchallengeable authority, as philosophers like Plato and Hobbes had tried to use it. Zamyatin wanted no part of this. In his 1920s anti-utopian novel *We,* a source for Orwell's *1984*, Zamyatin depicted individuals reduced to being numbers and mathematical tables of organization used as instruments of social control. The results were frightening (Zamyatin 1952). And mathematics and its applications were at their worst in the design of the Nazi death camps, where the analytical method was applied to the assembly-line production of corpses.

Yet the fruits of mathematics and mathematical reasoning are embodied in the idea of progress and in the advances in science and technology which have for the first time in human history made it possible, at least in theory, for all human beings to have decent food, clothing, shelter, and some leisure. The fruits of mathematics are essential to the triumphs of the scientific understanding of nature and in the use of science to liberate humanity from superstition. And the logic taught as part of mathematics is seen also in the working out of the consequences of the still radical idea that all human beings are created equal. Of course mathematics has not caused these changes all by itself. Still, it consistently has provided a powerful metaphor, reinforced by the historical authority possessed by the subject, both to drive and to legitimize these changes.

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[8] (Olson 2008, pp. 96–121; Richards 2002, pp. 11, 308–310). The Romantics would not admit that what epistemologists call "secondary qualities" like color, so constitutive of human experience, are mere epiphenomena reducible to "primary qualities" of matter in motion nor that greater understanding necessarily follows from mathematical description. As John Keats put it in criticizing "philosophy" (science) in his poem *Lamia* (part 2):

> Philosophy will clip an angel's wings,
> Conquer all mysteries by rule and line,…
> Unweave a rainbow.

Teachers and students need to know the ways mathematics has interacted with the full range of the liberal arts and to know both the power and the limitations of the claims of mathematics to truth and certainty and to universal applicability. Knowing these things, together with some mathematical proficiency, is needed to criticize what is wrong and develop further what is right in the liberal arts tradition and to use mathematics and its fruits to make real the idea of human progress. Teaching mathematics as a liberal art, then, is an important activity. And it is a global activity that transcends the West.

25.8 Mathematics Is Multicultural and Global

> There are others also that know something of value. – Severus Sebokht, c. 662 CE[9]

As the academic study of the liberal arts expands to include global history and anthropology, transcending the bounds of Western society, mathematics fits perfectly. Almost every society has mathematics and has mathematics that solves problems that the particular society thinks are important. Recent scholarship has shown that other cultures have sophisticated mathematical ideas and practices, though these have developed along different paths than in the West. The mathematics of other traditions than the Western can be used to gain perspective on these other societies, and anthropologists and global historians regularly use it this way. But the mathematics of other traditions also can be and is being used both to strengthen the teaching of mathematics and to humanize the subject.[10] The mathematics of other cultures can sometimes reveal the origin of modern mathematical ideas; can provide instructive examples of standard mathematical topics, advanced as well as elementary; can give teachers alternative ways of looking at familiar ideas; and can serve as a source of connection to mathematics for students of many different ethnic, religious, and national backgrounds. We shall look at each of these sources of insight in turn.

25.8.1 Roots of Modern Mathematics

Modern mathematics is not just Western in origin. Of course even the Greeks had important predecessors in Egypt and Babylonia. For instance, over a thousand years

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[9] (Joseph 2011, p. 462). Sebokht, a Syrian bishop, was challenging the supposed universal superiority of Greek scientific thought by praising the superior methods of calculation using the base-10 place-value number system from India.

[10] There is now an extensive and reliable English-language literature on the mathematics of other cultures. See, for instance, Ascher (1998, 2002), Berggren (1986), (2007), Closs (1986), Dauben (2007), Gerdes (1999), Gillings (1972), Imhausen (2007), Katz (2000), (2007), Martzloff (1997), Plofker (2007), (2009), Robson (2007), (2008), Robson and Stedall (2009), Van Brummelen (2009), and Zaslavsky (1999).

before Pythagoras, the Babylonians were aware of the Pythagorean rule for right triangles. They also developed sophisticated mathematical models to predict the motion of sun, moon, and planets, using the base-60 fractions which survive today as we divide degrees into minutes and seconds and which the Greek astronomers adopted as well.[11]

Mathematicians in the Islamic world brought together the computational traditions of the East and the geometric and proof-based methods of the Greeks into a new approach to the exact sciences (Berggren 1986, pp. 7–8; Høyrup 1994, pp. 100–103), further developing mathematical models in astronomy including some later used by Copernicus, classifying and then systematically treating the solution of all types of quadratic equations, and geometrically solving cubics (Berggren 1986, pp. 118–123; Berggren 2007, pp. 542–546; Katz 2009, pp. 287–292). At first motivated by the problem of finding the great-circle direction of Mecca from any point on the globe, Muslims greatly advanced the spherical trigonometry they had inherited from the Greeks (Berggren 1986, pp. 182–186; Van Brummelen 2009, pp. 194–201). Beginning from Indian work on what we call the sine and cosine, mathematicians in the Islamic world defined all six of the plane trigonometric functions and developed sophisticated approximation methods to produce trigonometric tables good to five base-60 places (Katz 2009, pp. 306–310). They also further studied the logical equivalents to the parallel postulate (Berggren 1986, pp. 13–15; Katz 2009, pp. 301–303). The important influence of these achievements of Islamic mathematics for later work in Europe, via the writings of Leonardo Fibonacci of Pisa in the thirteenth century and in translations from the twelfth century to the Renaissance, has been amply documented (Katz 2009, 317–318; Van Brummelen 2009, pp. 223–227).

25.8.2 Premodern Discoveries Around the World

Societies whose influence on European mathematics has been less direct, not yet documented, or even nonexistent have also developed sophisticated mathematics, often considerably earlier than did Europeans. For instance, in India combinatorics developed as early as the third century BCE, notably to explain how many different combinations of “heavy and light” (stressed and unstressed) syllables in a line of n syllables there could be. In the tenth century, the *meruprastara* (mountain-shaped figure, known now as the Pascal triangle) was developed to display the answers (Joseph 2011, pp. 352–355; Plofker 2009, p. 57). To describe planetary positions over time, Indian mathematicians worked to solve simultaneous numerical congruences, which in turn led them to give a complete theory of solving what is now called the Pell equation, long predating

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[11] See Katz (2009, pp. 17–18, 84–88), Robson (2007, pp. 100, 140–141, 151), and Robson (2008, pp. 109–115, 218–219).

the solutions in the eighteenth century by Euler and Lagrange (Katz 2009, pp. 246–250; Plofker 2007, pp. 423–433).

Indian plane trigonometry began by using Greek methods, but advanced the subject considerably. For example, long before Taylor series were known in the West, Indian trigonometry in the fourteenth century produced the infinite power-series expansions for sine and cosine, sometimes called the Madhava-Newton series after two of its independent discoverers (Katz 2009, pp. 257–258; Plofker 2009, pp. 236–246). Indian mathematics had both interactions with and direct influence upon mathematics in the medieval Islamic world (Plofker 2009, pp. 255–278).

In China, a classic work from before the second century BCE gave methods for solving simultaneous linear equations, using what we would call matrices or Gaussian elimination, and including an example of six equations with six unknowns (Dauben 2007, pp. 346–355; Katz 2009, pp. 209–212). In the eleventh century in China, one finds again the Pascal triangle of binomial coefficients; the coefficients were used to approximate the solutions of polynomial equations of arbitrary degree, in a way analogous to the modern method named after the nineteenth-century mathematician William Horner (Dauben 2007, pp. 329–330; Katz 2009, 213–217). In indeterminate analysis, the Chinese, like the Indians, were initially motivated by astronomical problems to solve simultaneous congruences, using a method which, after it became known in Europe in the nineteenth century, has been called the Chinese Remainder Theorem (Dauben 2007, pp. 302, 311–322; Katz 2009, pp. 222–225). Like mathematicians in India and in the Islamic world, the Chinese had a base-10 place-value system, and, like mathematicians in the Islamic world, the Chinese developed decimal fractions.

Mathematicians in the Islamic world also developed systematic combinatoric methods, including steps toward the method of proof now known as mathematical induction. Their mathematicians, as had those in India and China, developed the Pascal triangle of binomial coefficients (Berggren 1986, pp. 53–63; Katz 2009, pp. 282–296) and used it for, among other things, approximating n^{th} roots. They worked out what we now call the multiplication and division of polynomials – without the benefit of algebraic symbols – including the use of negative exponents. They were the first to recognize that decimal fractions are essentially polynomials using powers of 10 and that fractions can be represented as closely as one likes by taking sufficiently many decimal places (Berggren 1986, pp. 111–118; Katz 2009, pp. 279–282).

Combinatorics was developed also in medieval Jewish culture, where the initial purpose was to work out the number of possible Hebrew words in order to understand language and, therefore, since the Bible describes God creating the universe through speech, to understand creation. Levi ben Gershon (1288–1344) called the proof method he used for combinatorial results “rising step by step without end,” anticipating the idea of mathematical induction. Also, building on the discussions of Jewish law in the Talmud, medieval Jewish mathematicians anticipated the modern idea of expected value in discussing the problem of fair division (Katz 2009, pp. 337–338; Rabinovitch 1973, pp. 143–148, 161–164).

25.8.3 Pedagogical Insights from Around the World

Looking at alternative treatments from other cultures even of less advanced topics can add insight to the teaching of mathematics. Consider, for instance, what constitutes a proof. At least before the Jesuits brought Euclidean geometry into China in the seventeenth century, Chinese mathematicians did not use proof by contradiction, even though such reasoning is found in Chinese philosophy (Hanna and de Villiers 2012, pp. 431–440; Leslie 1964; Siu 2012, pp. 431–432). In China, mathematicians produced visually convincing proofs, including for the Pythagorean theorem (Dauben 2007, pp. 221–226, 282–288; Hanna and de Villiers 2012, pp. 431–440; Katz 2009, p. 237; Siu 2012, pp. 432–433). Chinese algebraists proved the validity of some algebraic algorithms by reducing them to other algorithmic results already known (Chemla 2012; Dauben 2007, p. 377; Hanna and de Villiers 2012, pp. 423–429). Going beyond proof methods, it is of pedagogical interest to contrast Chinese and Greek mathematical methods in a variety of contexts (Dauben 2007, pp. 375, 377; Horng 2000).

Indian mathematicians, like those of China, did not use postulates as a basis for their proofs, but like the Chinese, they systematically, though usually implicitly, assume that areas remain the same when dissected in different fashions, and provide rational justifications for a range of results, including the Pythagorean theorem (Plofker, pp. 247, 251).

Among other examples of non-Western materials that can add to the understanding of modern topics, consider how in India between the sixth and eighth centuries, long before the writings of Leonardo Fibonacci of Pisa, the Fibonacci series arose in answering a question about poetic meter.[12] The structure of the answer suggests that this series can solve a wider class of problems, as indeed later history shows that it does. And in the Islamic world, Euclidean geometric theorems about areas, used to justify the derivation of the algebraic technique of solving quadratic equations, are illustrated by the visual picture of completing the square, a picture that greatly enhances student understanding of the solution of quadratics (Berggren 1986, pp. 104–110; Joseph 2011, pp. 477–480; Katz 2009, pp. 272–276).

25.8.4 Mathematical Ideas from Many Cultures

Examples of topics now part of modern mathematics abound also in the mathematics of many of the cultures studied by modern anthropologists as well as that of other

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[12] The question is, if long or heavy syllables are two beats and short or light syllables are one beat, what is the number of different arrangements $A(n)$ of long and short syllables for a line of n beats? For example, if there are two beats and if we use “S” for short and “L” for long, the arrangements are SS and L. If there are three beats, the arrangements are SSS, SL, and LS. If there are four beats, the arrangements are SSSS, SSL, and SLS (formed by placing an S in front of each of the arrangements for three beats), plus LSS and LL (formed by placing an L in front of each of the arrangements for two beats). Thus, $A(4)=A(3)+A(2)$. Since $A(2)=2$ and $A(3)=3$ and since the method of forming $A(n)$ from $A(n\text{-}2)$ and $A(n\text{-}1)$ must follow the same pattern, this gives the Fibonacci series (Singh 1985).

ancient societies. These examples are often unexpected and therefore interesting to mathematicians as well as to anthropologists, linguists, artists, historians, and educators. For instance, the eminent algebraist André Weil has shown how the systems of marriage laws in some Aboriginal societies in Australia can be modeled by the theory of groups, and Marcia Ascher gives a variety of examples of such marriage laws, both in Australia and among the Malekula people of Vanuatu (Ascher 1998, pp. 70–81; Weil 1949, 1969). Not only is the Malekula system's structure isomorphic to that of the dihedral group of order 6, the Malekula themselves reason using a geometric diagram to describe, explain, and answer questions about their kinship relationships (Ascher 1998, pp. 77–81). Both the Bushoong people of central Africa and the Malekula can distinguish between graphs which have what are now called Eulerian paths and those that do not. The Bushoong use such graphs for purposes ranging from embroidery to political prestige (Ascher 1998, pp. 31–37), while the Malekula use knowledge of them in stories and myth (Ascher 1998, pp. 43–62). There are now several textbooks using such culturally based graphs and designs to teach mathematics; an excellent example is Gerdes (1999).

Geometric symmetries abound in the various artistic designs used in many cultures. The beauty of these designs makes them valuable examples in teaching about the structure of groups of symmetries (Ascher 1998, pp. 155–183; Washburn and Crowe 1998). And just as in classical Chinese and Indian civilization, modern mathematical instruction in the algebra of congruences and in astronomical models can draw on calendars from a variety of cultures that have chosen to deal in different ways with the different periods of the apparent motion of the stars, sun, moon, and planets. Comparing and studying the different calendrical systems used by, for instance, the Maya in the Americas; modern inhabitants of Bali; the ancient civilizations of Egypt and Babylonia, China, and India; and Jews, Muslims, and Christians, can link mathematics and astronomy to culture and religion (Ascher 2002, pp. 39–88).

Studying different number systems and different number bases becomes alive when linked to particular cultures, especially cultures related to one's students' own backgrounds. Examples interesting to US students can include the base-20 place-value system of the Maya and the sophisticated astronomical calculations for which it was used (Ascher 2002, pp. 62–74; Closs 1986), the multiplication by adding multiples of appropriate powers of two of the multiplicand used by the ancient Egyptians (Katz 2009, pp. 4–5), the variety of number bases used by different indigenous cultures of Africa (Zaslavsky 1999), and the base-60 place-value system of the ancient Middle East that gives us "modern" minutes and seconds.

The study of the mathematics of cultures other than the Western and interest in placing such mathematics in its cultural setting and using it to teach mathematical ideas and practices, all have attracted much interest in the past few decades. This approach has come to be called "ethnomathematics," a term introduced in D'Ambrosio (1985), and has generated a rich literature. For the purposes of the present essay, this brief sketch of some of the relevant mathematical ideas and practices will have to suffice, but as the sources cited in this section make clear, there is now a wealth of excellent scholarship devoted to mathematics in different cultures and time periods, regardless of whether or not that mathematics has influenced modern mathematics. The connection of mathematics with subjects ranging from anthropology to the visual arts is vastly enriched by a multicultural perspective. Here, then, is another important link between mathematics and the liberal arts, where in this case the liberal arts range far beyond the traditional texts of the Western canon.

25.9 Teaching Mathematics as a Liberal Art in the Modern University

After soaring into space with Euclid and Newton and Lobachevsky, roaming the globe and sampling mathematical thought across time and across continents, and after transforming world views with the architects and anthropologists, the philosophers, and theologians, let us come down to earth and enter a few classrooms in the English-speaking world, where, to quote the Yeats poem again, “The children learn to cipher.” Students are using the quadratic formula to solve $2x^2-11x+14=0$. For what purpose? Why does the formula work? Who thought it up, and why? Nobody says. The formula is rarely derived even algebraically, let alone in the intuitively pleasing way with the geometric picture of completing the square. A student recently told the author that he “knows” the quadratic formula because a teacher taught his class to sing it to “Pop Goes the Weasel.” In elementary schools, the rules of arithmetic are too often presented in the manner satirized as “Ours is not to reason why; just invert and multiply” (Wilson 2003, p. 6). Such methods of instruction may have been appropriate to produce a nineteenth-century nation of shopkeepers in an age without electronic calculators, but not to develop citizens who can independently apply mathematical and statistical reasoning to the quantitative ideas so pervasive in modern society and who understand the role of mathematics in the wider world.

Students need to know why, not just how, so that they can adapt what they have learned to new situations. Teachers need to know how young people learn and to know not only the elementary mathematics that they teach but also what it leads to and how it is used. The history of mathematics could help link mathematics with the rest of the world and to the rest of the liberal arts. But using algorithms, rather than being liberating and empowering as it was to seventeenth-century mathematicians, now has become a rule-based march toward the multiple-choice test.

The present chapter will not presume to prescribe solutions to the problems of pre-university mathematics education or to explain how to overcome the political and social forces that stand in the way of improving instruction, save to emphasize “For everything there is a reason” and to encourage teachers to explain the why as well as the how.[13] At the university level, those students specializing in

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[13] Discussions about how this can and has been done, and how it has been assessed, may be consulted in Alternatives for Rebuilding Curricula Center (2003), Ball et al. (2005), Boaler and Staples (2008), Hill et al. (2005), and Tarr et al. (2008). A cross-cultural study involving Chinese and American teachers at the elementary-school level can be found in Ma (1999).

science and mathematics will manage relatively well. Their professors will understand the mathematics, be able to answer student questions, and will point students toward real applications. Courses in the history and philosophy of mathematics can help mathematically literate students see the kinds of links described in the present paper. But what of the self-defined liberal arts student, who comes to the university definitely wanting *not* to study mathematics? This essay will conclude by addressing this question.

A common practice in many American colleges and universities is to teach all these students precalculus. This usually repeats what did not work for them in high school. Such an approach frustrates students and teachers alike, and a terminal precalculus course seems to defeat any logical purpose. Another approach is to use one of the textbooks designed to teach mathematics to liberal arts students (e.g., Burger and Starbird 2012; Jacobs 2012), or the applications-oriented book *For All Practical Purposes* (COMAP 2013) and others that resemble it. Such texts have been successful in a variety of universities, and those who find the books successful with their own students should of course use them and recommend them to colleagues.

But for those who find the story told here sufficiently compelling to try to design their own courses for liberal arts students, some principles useful for classes designed by individuals are worth considering. First, base the course on something of interest to contemporary students in which the instructor has expertise, whether it is "mathematics and art," "games and gambling," or "mathematics in many cultures."[14] After all, mathematics was considered important and interesting throughout history because people wanted to solve particular problems, some within mathematics itself, some of importance to the wider society. Teaching what instructors themselves find interesting and exciting recapitulates the history of mathematical creativity.

Second, although the mathematics chosen must be accessible to liberal arts students, it should also be important mathematics in the eyes of mathematicians. The liberal arts goals require this. Third, for students who will probably never take another mathematics course, learning mathematics should be empowering, not overwhelming. It is more important for them to be able to use the mathematics they know than to be shown more mathematics that they cannot master. A liberal arts course isn't prerequisite to anything. There is merit in going slowly enough so that 90 % of the students will get 90 % of the mathematics. This lets them, perhaps for the first time, experience mastery in mathematics; this is part of understanding what mathematics is all about. "I get it now" is a necessary prerequisite for seeing the beauty and elegance of mathematics, and also of being able to apply it to a new situation.

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[14] Examples of books that might be suitable for such courses include Ascher (1998 and 2002), Frantz and Crannell (2011), Gerdes (1999), and Packel (1981). For details about the author's courses, see Grabiner (2011). A superb online resource for liberal arts mathematics teaching is the Mathematical Association of America's "magazine" of the history of mathematics and its uses in the classroom, *Convergence* (n.d.).

Fourth, all students have expertise. It may not be in mathematics, but they do have expertise in their major or some outside interest. A liberal arts course should allow each student to build a course project incorporating that expertise and thereby impress and teach everybody else, sharing their course projects with each other in the class. This will produce many more applications of mathematics than most professors could generate and a surprising range of fascinating mathematical topics. Just as in the case of the instructors teaching what interests them, the depth of the individual student's excitement about the topic will enhance that student's learning. And the individual student becomes the class expert on one piece of mathematics, perhaps for the first time in that student's life.

Students often identify mathematics with number and calculation alone or perhaps with elementary geometry and trigonometry. In modern times, though, because of the increasing abstraction of contemporary mathematics and because many branches of mathematics, from topology to infinite-dimensional spaces, transcend ordinary experience, a broader characterization of mathematics has developed. In the recent influential words of Lynn Steen, "No longer just the study of number and space, mathematical science has become the science of patterns, with theory built on relations among patterns and on applications derived from the fit between pattern and observation" (Steen 1988, p. 611). "Pattern" is a valuable metaphor in accounting for the applicability of mathematics, since mathematical patterns can mesh with the patterns of order of the universe. But the metaphor also underscores the beauty of mathematical ideas, linking mathematics in a different way to the rest of the liberal arts. As G. H. Hardy, perhaps the earliest to use the idea, put it, "A mathematician, like a painter or a poet, is a maker of patterns…. The mathematician's patterns, like the painter's or the poet's, must be *beautiful*; the ideas, like the colours or the words, must fit together in a harmonious way" (Hardy 1967, pp. 84–85, italics his).

Faculty members at many institutions may not have the freedom to invent new courses, but the general principles should help every teacher of mathematics for non-mathematicians. Mathematics is fun and exciting, both beautiful and useful. It makes unique claims to truth, is governed by logic and reason, and has interacted with every conceivable subject. It has been created by human beings all over the world, in the past and in the present, by men and by women.[15] To be able to follow logical arguments and to criticize them is liberating; as Jacques Barzun observed, "The ability to feel the force of an argument apart from the substance it deals with is the strongest possible weapon against prejudice" (Barzun 1945, p. 121). It is liberating to have understood the "why?" rather than just to have memorized processes, so that people can use the mathematics they know to analyze ideas and solve problems they have never encountered. Mathematics matters not just to stu-

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[15] On women in mathematics in general, see the online biographies maintained by Agnes Scott College (2012), the sourcebook Grinstein and Campbell (1987), and the Mathematical Association of America's poster *Women of Mathematics* (MAA 2008). On important individual women in mathematics, see Arianrhod (2012), Brewer and Smith (1989), Dahan-Dalmédico (1991), Deakin (2007), Hagengruber (2012), Katz (2009, pp. 189–190, 616–617, 714–715, 787, 874, 896–898, 899), Koblitz (1983), Mazzotti (2007), Neeley (2001), Reid (1996), and Zinsser (2006).

dents but to all members of a free society. As this essay has argued, mathematics lies at the heart of the ancient and medieval liberal arts and of those fields called liberal arts today. Viewing mathematics as a liberal art shows both why mathematics is important and how it should be taught.

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Chapter 26
The Role of History and Philosophy in University Mathematics Education

Tinne Hoff Kjeldsen and Jessica Carter

26.1 Introduction

In this chapter we discuss the roles of the history and philosophy of mathematics in the learning of mathematics at university level. University mathematics is organised differently in different universities and countries. In some universities mathematics is separated into different programmes: masters in pure mathematics, in applied or industrial mathematics, in financial mathematics, in teacher training education, etc. In this paper we consider mathematics programmes that lead to a graduate degree in mathematics, i.e. mathematics programmes where pure mathematics plays an essential role.[1] In the context of the present handbook, the following three questions immediately come to mind: (1) Why do we need a chapter that focuses especially on mathematics? (2) Why do we need a chapter that focuses especially on university level mathematics? (3) Why combine history and philosophy?

The first question has also been addressed by Michael N. Fried in the Chap. 21. Fried pointed out that there are differences between the sciences and mathematics that justify the inclusion of this question in the present handbook of separate chapters focusing on history and philosophy of mathematics in mathematics education. Here we will mention the picture of mathematics as the epitome of timeless truths and mathematical objects as ideal, timeless entities – named by some as an

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[1] For the roles of the history and philosophy of mathematics in liberal arts education, we refer to the previous chapter by Judith Grabiner.

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absolutist philosophy of mathematics. One consequence of this picture, which is conveyed to students by traditional mathematics educations at all levels (François and Van Bendegem 2007), is that it portrays mathematics as a cumulative science of a seemingly static and infallible character of knowledge (Otte 2007, p. 243).

An essential difference between the history and philosophy of mathematics in primary and secondary mathematics education and mathematics at university level is that at university level these subjects often have their own courses within the mathematics programme: with their own learning goals, curriculum, disciplinary standards and agendas which are not restricted by a mathematics curriculum that has to be taught in the same courses as well. Hence, the history and philosophy of mathematics can play very different roles in mathematics education at the university level than at the primary and secondary level. These differences justify a separate chapter within the present handbook that focuses on the university level.

Finally, during the past few decades, research in the history and philosophy of mathematics has witnessed a trend towards a focus on mathematical practices from which historical and philosophical investigations and analyses have taken a point of departure. On the one hand this has strengthened the relationship between the professional academic disciplines of history and philosophy of mathematics, with historical investigations serving as cases for philosophical studies and vice versa philosophical ideas serving as inspiration and tools for historical analyses.[2] On the other hand, studying the history and philosophy of mathematics from the practices of mathematics brings these subjects close to mathematical research activities, to processes of knowledge production in mathematics and hence to mathematics education at university level. It therefore makes sense to look at the history and philosophy of mathematics in a common perspective in relation to the roles they (can) play in mathematics education at university level.

In the following we first briefly introduce a historiographic framework of a multiple perspective approach to the history of mathematics from its practices together with some reflections about uses of history, and we introduce the direction of research in the philosophy of mathematics that is denoted 'Philosophy of Mathematical Practice'. We then link the history and philosophy of mathematical practices to recent ideas in mathematics education in order to identify different roles history and philosophy can play in mathematics education at university level. This is followed by presentations, analyses and discussions of different examples of the inclusion of history and philosophy in university programmes in mathematics. These presentations are divided into courses in history and philosophy, since this is the main way they are organised at the universities. We shall see, however, that the history courses address philosophical questions and that the philosophy courses employ historical material. The chapter is rounded off with comments on how mathematics educations at university level can benefit from history and philosophy of mathematics.

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[2] Our joint paper (Kjeldsen and Carter 2012) serves as an example of this mutual beneficial relationship.

26.2 History and Philosophy of Mathematics from Its Practices

The history and philosophy of mathematics are two independent professional disciplines that have followed their own trajectories. As mentioned in the introduction, during the past few decades the research in the history and philosophy of mathematics has witnessed a trend towards a focus on mathematical practices. In the following we will introduce a historiographical framework of a multiple perspective approach to history of mathematics from its practices and introduce one direction of research in philosophy of mathematics that is denoted ‘Philosophy of Mathematical Practice’. These are methodological issues in the professional disciplines of history and philosophy of mathematics. In mathematics education at university level, approaches to history can be found that are not necessarily aimed at purely historiographical goals, but are directed towards the teaching and learning of mathematics. In order to analyse such approaches, we also introduce parts of a framework for uses of the past.

26.2.1 History of Mathematics from Its Practices and Uses of the Past

Research into people’s uses of history has shown that people use history in many different contexts, for different purposes and with different approaches; see, e.g. Ashton and Kean (2009) and Jensen (2010). In this context, the Danish historian Eric Bernard Jensen conceive of history as an umbrella term for related forms of knowledge and practises people uses in their lives, and he defines history accordingly by saying that we are dealing with history ‘when a person or a group of people is interested in something from the past and uses their knowledge about it for some purpose’ (Jensen 2010, p. 39). Historians (or users of history) might have different perspectives on history depending on their aims. This is also the case for history of mathematics which is, and has been, studied and used in different contexts with different goals.[3] In his book *What is History*, Jensen (2010) provides a framework in which different uses of the past can be characterised. The framework can be used to analyse and characterise implementations of history in mathematics education. Here we will only introduce his distinction between a *pragmatic* and a *scholarly* approach to history.[4]

A historian who studies history from a utility perspective is said to have a *pragmatic* approach to history. It is an approach in which history is conceived of as ‘the master of life’, i.e. we can learn from history. In a pragmatic approach to history,

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[3] See, e.g. Lützen and Purkert (1989) where the different historiographical views of Cantor and Zeuthen are discussed.

[4] In Kjeldsen (2012) Jensen’s terminology is outlined and used as lens through which we can identify and distinguish between different conceptions and uses of history of mathematics.

the historian will try to make history relevant in a present-day context. In Jensen's terminology, historians who focus on understanding and interpreting the past on its own terms, regardless of the present situation, is said to have a *scholarly*[5] approach to history. According to Jensen the scholarly approach has been the dominant one in academic, professional history since the mid-nineteenth century.

In the following we will present a multiple perspective approach to history of mathematics from its practices. The multiple perspective approach to history is inspired by Jensen's (2003) thinking about historiography. His underlying premise is that people produce history and are shaped by history. In order to understand social-historical processes and gain insights into the past, history is studied from perspective(s) of the historical actors. The historian pays attention to the historical actors' motivations, their projects, their intentions as well as unintended consequences of their actions. The perspective of the actors is taken into account which means that perspectives such as the actors' placement in space and time, in a certain society and/or in a particular intellectual context are considered as part of historical investigations.

If we think of mathematics as a historical and cultural product of knowledge that is produced by human intellectual activities, then a multiple perspective approach to history can be adapted to historiography of mathematics. Studying the history of mathematics then also involves searching for explanations for historical processes of change, such as, but not limited to, changes in our perception of mathematics as such, in its status and function in society, in our understanding of mathematical notions or objects and in our idea of what counts as legitimate arguments for mathematical statements.

Studying processes in the development and shaping of mathematics from mathematical practices means asking why mathematicians introduced specific concepts and definitions; why they studied the problems they did, in the way they did; and what were the driving forces behind their mathematical investigations; see, e.g. Epple (1999, Chap. 1) and Epple (2004, p. 133). One approach is to study concrete episodes of mathematical research activities focusing on the 'workplace' of the involved mathematicians in order to uncover and understand the dynamics of the knowledge production. The methodological framework of epistemic objects, techniques and configurations (Epple 2004), originally developed by the philosopher of science Hans-Jörg Rheinberger (1997), has been used recently in the historiography of mathematics; see Epple (2004, 2011) and Kjeldsen (2009). In short, epistemic objects refer to the mathematical objects about which new knowledge is searched for. Epistemic techniques refer to the methods and mathematical techniques that are used to investigate the mathematical objects in question; and epistemic configuration of mathematical research refers to the total of intellectual resources present in a specific episode. These terms are not intrinsically given, but are bound to concrete episodes of mathematical research. They are to be understood functionally, they change during the course of mathematical research and they might shift place. They are excellent tools for analysing the production of knowledge and the understanding of mathematical

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[5] This is our translation of the Danish word 'lærd'.

entities in historical texts, because they are constructed to differentiate between how problem-generating and answer-generating elements of specific research episodes functioned and interacted. In Kjeldsen (2011a) it is suggested how this framework can be used in connection with student project work in history of mathematics for the learning of and about mathematics in university mathematics education.

In bridging the history of mathematics with mathematics education, we find a multiple perspective approach to the history of mathematics, from its practices, that is particularly relevant to mathematics education at university level. This is due to its striving for understanding the dynamics of mathematical knowledge production, the status and functions of mathematics in society and in concrete episodes from the past. This will be discussed below in the examples from our own approach of specific implementations of history in mathematics programmes at university level.

26.2.2 Philosophy of Mathematical Practice

Similar to the history of mathematics, the philosophy of mathematics poses different kinds of questions and offers ways of dealing with these. New questions may arise because of changes in the practice of mathematics, and changes in perspectives are often the outcome of perceived limitations of previous methods. At present there is a growing interest in what is denoted ‘Philosophy of Mathematical Practice’. There are many motivations for this shift in interest; some are indicated below. Since this perspective is our focus, we will describe it in more detail.

It is no easy task to define philosophy. One way to describe it is that it poses fundamental questions concerning the world and our place in it. In addition philosophy seeks to answer these questions and, equally important, find arguments for the given answers. Philosophy – unlike mathematics – is a discipline where there seems to be very little agreement about answers. This does by no means entail that ‘anything goes’. There are certain standards measured, for example, by the coherence of one’s proposal, soundness of arguments as well as quality and sensibility of assumptions. Ideally, philosophy should advance our knowledge by critically examining our ideas, assumptions and arguments. Mathematics also gives rise to philosophical queries. Traditionally, philosophers have mainly asked questions within ontology and epistemology: questions such as ‘What kind of entities are mathematical objects?’ and ‘Do they exist independently of the activities of human beings?’ and epistemological questions like ‘how do we obtain knowledge in mathematics?’ Philosophers at all times have been fascinated with the apparent necessity of mathematical truths and the fact that mathematics is applicable to the real world while its subject matter seems remote from anything real. Philosophers such as Plato, Aristotle, Descartes, Kant and Mill all found that something should be said about mathematics.[6]

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[6] Their views on mathematics are very different. For a presentation of their positions, see Shapiro (2000). For a nontraditional description of Plato’s philosophy, in line with the perspective of mathematical practice, see McLarty (2005).

During the nineteenth century, mathematics changed drastically. From being conceived as somehow describing the real world, mathematics changed into an autonomous body of its own ideas. Gray (2008) characterises modern mathematics as being remote from the real world, having a strong 'emphasis on formal aspects of the work and maintaining a complicated – indeed anxious- rather than a naive relationship with the day-to-day world' (p. 1). For one thing, these changes led *mathematicians* to pose fundamental questions regarding the nature of mathematics and – perhaps more importantly – concerning how to obtain a secure foundation.[7] These questions led to the three foundational schools, Logicism, Intuitionism and Formalism; see, e.g. Benacerraf and Putnam (1983), Mancosu (1998), and van Heijenoort (1967). Outcomes of these programmes were the development of logic and proof theory[8] as well as a (one-sided) focus on questions pertaining to the justification of mathematics. Philosophy of mathematical practice can be seen as a reaction to the philosophers' one-sided stress on formal mathematics. Among the first to enter this lane was Lakatos (1976) who found that answers could be found by studying the practice of mathematics, writing (explicitly referring to Kant's famous line from Critique of Pure Reason A51,B75) 'Philosophy of science without history of science is empty; history of science without philosophy of science is blind' (Lakatos 1970, p. 91). Lakatos held that philosophy should also deal with questions concerning discovery or more precisely he argued that the processes of discovery and justification are intertwined. This approach to the philosophy of mathematics has gradually increased in popularity. Pioneers are Kitcher (1984), Maddy (1990), Tymoczko (1985), and later Corfield (2003). In what could be denoted as 'Philosophy of mathematical practice' today,[9] a (rough) distinction can be made between three approaches. These outlooks can be termed social, historical and epistemological. Since our approach to the philosophy of mathematics lies mainly within the epistemological strand, we describe this in more detail below.

The strand that has a sociological focus takes as a starting point the view that mathematics is a human activity (Hersh 1979) and as such can be described by sociological tools (Heinz 2000). Others are closer to mathematics education; see

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[7] Another interesting development in mathematics around the turn of the century was the move towards structuralism. What is studied in mathematics is not the objects as such – it is the relations between objects. This is most famously described by Hilbert saying 'one must be able to say "tables, chairs, beer-mugs" each time in place of "points, lines, planes"' (Blumenthal 1935, pp. 402–403), expounded mathematically in his Foundations of Geometry (Hilbert 1899). Traces of this conception about mathematics can still be found in today's philosophies of mathematics; see Benacerraf (1965), Hellman (1996), Resnik (1999), and Shapiro (1997). More recently philosophers have argued that category theory provides a sound basis of a 'top-down' structuralist view (Awodey 1996; Landry and Marquis 2005).

[8] Since the original foundational schools failed for a variety of reasons, other ways of obtaining a foundation were looked for. It was, for example, proved by Gentzen during 1930s that if sufficiently strong methods (induction over ε_0) are used, then it is possible to prove the consistency of arithmetic. A different approach is to find a weaker system than Primitive Recursive Arithmetic where completeness and consistency are provable.

[9] See, e.g. Ferreiros and Gray (2006), Mancosu (2008), Van Kerkhove and Van Bendegem (2007), and Van Kerkhove et al. (2010).

Bloor (1994), Ernest (1998), and Restivo (1993). This outlook is also the basis of the fairly recently formed Phimsamp group.[10] It is already integrated with mathematics education, especially through the work of Ernest (see http://people.exeter.ac.uk/PErnest/ and references throughout this chapter).

The second strand has history of mathematics at its core. One such perspective notices that mathematics itself at different times has posed philosophical questions and seeks to bring out the historical circumstances for these questions. This was the case in the period during which the foundational schools were formed – and as noted above, the people asking the questions and providing answers were in fact mathematicians themselves. A nice example of this outlook is presented by J. Tappenden (2006). He shows that there are certain misconceptions regarding Frege's mathematical motivation for engaging in his project.[11] Another perspective deals with the philosophical conceptions of the mathematicians themselves and how these conceptions help form the development of mathematics.

The final strand asks traditional philosophical questions and seeks answers to these by considering mathematical practice. Mancosu (2008) presents a number of excellent papers within this strand. For us taking this approach means that both questions and means for answering these questions are taken from mathematical practice. We acknowledge that questions may arise within mathematical practice itself and that assumptions should to some extent agree with practice. This is in part a reaction to traditional philosophical approaches, where one starts with an assumption about mathematics, such as 'mathematical statements are necessarily true', and then argues that it follows that mathematical objects exist (by necessity). There are two objections to this procedure. First, mathematics itself is missing from the picture. Second, the assumption needs to be examined. It is not clear whether mathematical statements are necessary or, if so, in which sense they are necessary (Carter 2008). When taking this approach, the aim is to obtain a better understanding of the mathematics that we (as human beings) know and use. The focus of Carter is to understand better contemporary mathematics; but in principle any part of mathematics could be the object of study. Which practice – or case – to study depends (in part) on which question is posed. This approach also has as consequence that it may not make sense to talk about the 'right' picture. Instead one may talk of useful pictures, in terms of determining for a given picture what is achieved by adopting this picture. We are still concerned about the coherence of pictures of mathematics, and that sound arguments should be provided. Thus in addition to the triple of standards – sensible assumption, valid arguments and coherent theory – a fourth component is added, namely, value of theory to a practice. This outlook may not be so different from the social outlook. A major difference concerns the set of

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[10] Philosophy of Mathematics: Sociological Aspects and Mathematical Practice.

[11] One misconception is that when Frege started worrying about the foundation of analysis, it had already been settled by the work of Weierstrass in Berlin. The fact of the matter, Tappenden argues, is that problems of *real* analysis were being solved, but Frege knew of the (revolutionary) work of Riemann from the 1850s integrating geometry and complex analysis, opening up whole new fields of study.

assumptions built in. On the social outlook, for example, it would be assumed that there exist a community of learners and teachers (Ernest 2009) and some mathematics, created by human beings, which need to be taught/learned. In addition it is a helpful assumption when teaching mathematics that communication is possible (Carter 2006). Our interest focuses on the nature of mathematical objects and development of mathematics in general and thus implicitly requires the assumption of the existence of mathematicians doing mathematics. On this perspective, the relevant practices to study are the different contexts in which mathematics is developed. It is also important to note that what we study is *how we humans acquire knowledge of mathematics*. By doing this, our intention is not to assume anything about the true ontology of mathematics.

Since we take as a starting point mathematical practice, the history of mathematics is an important ally in providing case studies. The dependency relation, however, is a two-way relation which was already pointed out by Lakatos. Even though philosophy and history 'feed on each other', our aims are different. The philosopher tries to establish whatever general can be stated by considering particular cases. But sometimes interesting things can also be said about the particular cases – see below for an example. In contrast, the historian seeks to bring out the particular in each practice. As argued in the section above, when doing this the historian needs certain (philosophical) tools or concepts. To conclude this section, we give an example of how this 'philosophy' works in practice. When addressing the question concerning the nature of mathematical objects, a way to obtain an answer is to look into the practice of introducing mathematical objects (Carter 2004). As a result of such studies,[12] Carter (2013) concludes that mathematical objects are often introduced with reference to, or even as representations of, already accepted objects. The importance of contexts both for introducing objects and reasoning with them is also pointed out. These are general categories that can again be tested against historical studies. The aim of Kjeldsen and Carter (2012) is to test these claims against a case study on the introduction of convex bodies in the work of Minkowski. We find that overall this case fits the given description. In addition we find that the cases display important differences, which also provides insight about the general development of mathematics. One such difference concerns the type of relation between the new object and its referent. The convex body is defined as a set having certain properties singled out as important when solving problems within number theory, whereas a Riemann surface is an actual representation of part of the defining expression of an Abelian function.

When teaching the philosophy of mathematics for university students, we find that it is particularly important that this teaching takes as its starting point the actual *practices* of doing mathematics. In their ordinary mathematics courses, students are exposed to one picture of mathematics. We believe they should be exposed to different pictures. We stress, though, that students should also be aware that different pictures have different assumptions and that these are, useful or not, merely *assumptions*.

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[12] The introduction of Riemann surfaces and K-theory.

26.3 History and Philosophy in Mathematics Education: Mathematical Competence, Critical Mathematics Education, Interdisciplinarity and Thinking as Communicating

In this section we link history and philosophy of mathematics with conceptions of mathematics education and learning in order to identify different roles history and philosophy can play in mathematics education at university level.

The cultural argument for mathematics in education and a need for students to develop interdisciplinary competences both provide roles for the history and philosophy of mathematics in mathematics education. Mathematical knowledge is a historical and cultural product of human intellectual activity. Its development and thoughts are tied to arts, philosophy and science. By integrating history and philosophy in mathematics education, the cultural argument for mathematics in education is emphasised. Through interdisciplinary teaching, history and philosophy can play a role in mathematics teaching and learning in developing students' interdisciplinary competences by counteracting disciplinary narrow-mindedness (Beckmann 2009).

Both of these roles for the history and philosophy of mathematics in mathematics education are embedded in the competence-based view of mathematics education as developed by Mogens Niss (2004) in the Danish KOM-project.[13] In Niss' competence-based description of mathematics education, mathematics curricula on all levels are based on mathematical competencies instead of a catalogue of subjects, notions and results. In the KOM-project, eight main competencies were identified. They are divided into two groups: (1) a group that has to do with the ability to ask and answer questions within and with mathematics (thinking, problem tackling, modelling and reasoning competencies) and (2) a group that concerns abilities and familiarities with language and tools in mathematics (representing, symbol and formalism, communicating, aids and tools competencies). Besides developing students' mathematical competencies, mathematics education should also provide students with three second-order competencies, so-called overview and judgement, regarding mathematics as a discipline. The first concerns actual applications of mathematics in other areas, the second concerns the historical development of mathematics in culture and societies, and the third concerns the nature of mathematics as a discipline. The second one explicitly requires knowledge about history of mathematics, though not as an individual discipline (the goal is not to educate competent historians of mathematics), but to develop students' overview and judgement regarding the historical development of mathematics resting on concrete examples from the history of mathematics. The third one explicitly requires knowledge related to the philosophy of mathematics. In the examples of actual implementations and incorporations of history and/or philosophy of mathematics given in the next section, we will discuss the

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[13] The project was called Competencies and Mathematical Learning. It was initiated by the Danish National Council for Science Education in 2000. For a shortened English version of the original report, see Niss and Højgaard (2011).

roles history and philosophy of mathematics (can) play in university mathematics programmes in the framework of mathematical competence.

The three types of overview and judgement concern the character of mathematics and its functions and roles in the world. This relates to issues that have been raised and researched in the field of critical mathematics education. In his paper 'Critical mathematics education for the future', Ole Skovsmose (2004, p. 10) points towards

> an important concern in mathematics education: Mathematics must be reflected on and criticised in its variety of forms of actions.

One of the aims in critical mathematics education is to develop in students the ability to critique the uses of mathematics. This relates to the first of the second-order competencies introduced above. In the next section we give an example of how history can function in mathematics education at university level with authentic cases that have the potential to develop students' ability to critique the uses of mathematics. Since critique is at the core of philosophy, it is also developed in the philosophy courses.

The last theoretical framework from mathematics education that we want to link to the role history of mathematics can play in mathematics education, is Anna Sfard's (2008) *Theory of thinking as communicating*. In Kjeldsen (2012) it is argued that, within this theory, history of mathematics can function at the core of what it means to learn mathematics. Sfard defines thinking as 'the individualized version of interpersonal communication' (Sfard 2008, p. xvii). Her theory is also referred to as the theory of commognition where the term commognition captures the combination of communication and cognition. Mathematical thinking is a human activity and Sfard treats mathematics as a type of discourse, where discourse 'refers to the totality of communicative activities, as practiced by a given community' (Sfard 2000, p. 160). Learning mathematics means to become a participant in mathematics discourse. Discursive patterns are the results of communicative processes that are regulated by rules. Sfard distinguishes between object-level rules and meta-level rules of mathematics discourse. Object-level rules concern the content of the discourse. Meta-level rules have the discourse itself as an object. They govern 'when to do what and *how* to do it' (Sfard 2008, pp. 201–202) – they are implicitly given. To develop proper meta-level rules is essential for becoming a participant in mathematics discourse. It is an important aspect of teaching and learning mathematics to create situations where meta-discursive rules are exhibited and made into explicit objects of reflection for students. These rules are contingent. They develop and change over time and as such they can be subject to historical investigations.

This is demonstrated in Kjeldsen and Blomhøj (2012) and Kjeldsen and Petersen (forthcoming) where it is shown how historical sources, investigated and interpreted within the mathematical practice of the historical actors, can function as 'interlocutors' that are following a set of meta-level rules within the mathematical community of their times. Through such historical investigations, students can become confronted with differences in metarules between rules that governed the mathematician(s) of the past episode they are studying, their own (maybe) and the rules of their textbooks and/or their teacher. In this way, meta-level rules can be revealed and turned into objects for students' reflections. This will be illustrated by one of the examples given in the next section of some students' investigations of a concrete mathematical episode from the past. From a philosophical view, we note that Sfard's position is just *one* possible view about mathematics in line with a social outlook on mathematical practice.

Within general mathematics education, philosophy of mathematics plays different types of roles. It is generally acknowledged that the teacher's conception of mathematics forms his or her teaching; see, e.g. Hersh (1979) and Lerman (1990). Chassapis (2007) therefore argues that it is relevant to train teachers in some kind of philosophy of mathematics and also shows one way to do it. Correspondingly it is also acknowledged that students' beliefs[14] on mathematics influence their learning. Prediger (2007) convincingly shows how addressing themes from philosophy of mathematics help pupils make sense of mathematical problems. She even argues that philosophical reflections *must* play a prominent role in the learning process.

With respect to beliefs about mathematics, two major camps are usually described. The discussion between these two sides is termed the 'science wars' (Ernest 2004). In one camp are the 'absolutist' views; these are often taken to include Platonism and Formalism. Ernest (1994) describes it as the 'Euclidean paradigm of mathematics as an objective, absolute, incorrigible, and rigidly hierarchical body of knowledge' (p. 1). In the other camp are the 'fallibilist' views. The often mentioned hero of this programme is Lakatos (1976). Other fallibilist views include Ernest (1998) and Bloor (1994), i.e. views that stress that mathematics is created by human beings and mathematical knowledge is as fallible as the rest of our knowledge. As a reason for the shift from absolutist views to fallibilist views is pointed to 'Gödel's theorems' which show that 'formal axiomatic systems can never be regarded as ultimate' (Ernest 1994, p.1). Another reason (which is more in line with the outlook of this paper) is the desire for a philosophy to pay attention to mathematical practice.

The roles philosophy play can be divided into three levels: the level of the individual, mathematics and society. On the mathematical level, one could claim that pupils/students should be able to reflect on the nature of mathematical objects and knowledge. As we have seen above, it is argued that such reflections are vital for both the learning and teaching of mathematics. On the level of society, as indicated above, educators have pointed to the social and political role that mathematics education (can) play. The 'Mathematics Education and Society' (MES) conferences were started in 1998 in Nottingham, UK, in order to focus on these roles. This perspective believes that there is much more to be said in mathematics education than a narrow picture of learning accomplished by an interrelation of the mind of a learner and (the value free and objective) mathematics to be learned. For one thing, it leaves out the class room and the teacher and the social relations between these which also affect learning. On a much broader scale are questions pertaining to the role of mathematics education in a particular society, such as who is included and what determines whether you are 'in' or 'out'? In some (most?) countries

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[14] It is generally held that students' beliefs influence their learning, for example, that affective beliefs play a major role (Burton 2004). Here we are only interested in philosophical beliefs.

knowledge of mathematics is a ‘gatekeeper’ to the inclusion of the society (see Skovmose 2004). We will not delve more on these roles, but merely state that they are important and complex. Skovsmose (2004), for example, describes how mathematics education can empower or disempower, include or exclude and discriminate, advancing what he denotes critical mathematics education. Finally, at the level of the individual, it could be the case that awareness of philosophical matters concerning mathematics could help the individual learn and – as we will discuss later – even become better mathematicians.[15]

On the actual implementation of philosophy in the teaching of mathematics, not much is written. In secondary level mathematics, Flanders, François and Van Bendegem (2010) conclude there is little room for philosophy of mathematics. Concerning philosophy of mathematics for university education, the authors ask:

1. Is there room for philosophy of mathematics at university level? We answer YES!
2. If so, what kind of philosophical approach? Should one stress the fallibility of mathematical knowledge, should one stress the social nature of mathematics or should one stress the curious mechanisms that have led to such a strong consensus among mathematicians (François and Van Bendegem 2010)? We answer neither! All pictures could be presented. The point would be to introduce the questions to which these are answers as well as tools to deal with them, so that students may form their own conclusions.

In this chapter our task is to consider implementation and possible roles for history and philosophy for university mathematics students. It seems clear that these students must be considered among the included people of the society. They already know how to learn mathematics, and hopefully even like it. The role that philosophy should play in university education is thus clearly different. However, the roles introduced above are relevant in the following ways. We will argue below that both philosophy and history of mathematics will make mathematics students better as mathematicians, not necessarily because they learn more mathematics, but since they will be able to get a wider picture of their subject. We also find that mathematics students should *be made aware of* some of the social implications of mathematics, even though they themselves may not personally be affected by them. We return to a discussion of these roles when we have presented actual examples of implementing courses in history and philosophy of mathematics.

26.4 Examples of History in University Mathematics Programmes

In this section we will present and discuss some specific implementations of history in mathematics programmes at university level. We have chosen three examples that illustrate different ways and approaches of integrating history as well as different

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[15] It has also been argued that knowledge of philosophy can turn you into a better person. Philosophy teaches rational thinking, and in particular, ethics deals with the good and bad.

roles history plays in these programmes. The third example comes from our own approach and will be treated in more depth. The examples will be presented, analysed and compared with respect to their aims, their learning objectives, their use of sources and the significance of history. The function of history in these implementations will be analysed within the conceptions of mathematics education and learning of mathematics that were introduced above. We will point out and explain situations where we find the approach of history and philosophy of mathematics from the perspective of mathematical practices particularly relevant for mathematics education at university level.

26.4.1 Ex. 1: History of Mathematics 1: Copenhagen University

History of Mathematics 1 is a course that is offered in the mathematics programme at Copenhagen University, Denmark. It has been developed and taught by Jesper Lützen, who is a historian of mathematics. The history course is placed at the bachelor's (undergraduate) level in the mathematics programme. The students who follow the course are mathematics students, who will finish with a university degree with a master's in mathematics or a master's in another subject and a bachelor's in mathematics. The study programme in mathematics is not divided into pure, applied or teacher education programmes, but History of Mathematics 1 (or a similar course in the history of mathematics) is required for students who (later on) decide to become high school teachers in mathematics.

The course is a general history of mathematics course and its main purpose is to teach a survey of the history of mathematics from ancient times to the present. The course book is Victor Katz's (2009) *A History of Mathematics: An Introduction* which is supplemented with a booklet (Lützen and Ramskov 1999) with selected sources and exercises comprised and developed for the course. The objectives of the course are formulated in terms of what the students should be capable of doing after following the course, namely, to[16]:

1. Communicate orally as well as in written form about the history of mathematics
2. Use the history of mathematics in connection with mathematics teaching and more generally reflect on the development of mathematics
3. Place a concrete piece of mathematics in its historical context
4. Find literature (primary as well as secondary) on the history of mathematics
5. Give a historical analysis of a mathematical text from the past
6. Independently formulate and analyse historical questions within a limited field
7. Use the history of mathematics as a background for reflections about the philosophical and social status of mathematics

These objectives are reached on one hand through broad lectures on various cultures and time periods following (more or less) the outline of Katz's book

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[16] http://sis.ku.dk/kurser/viskursus.aspx?knr=121117&sprog=2&forrige=57876

and on the other hand through a small group-organised project work on either tangent and max-min methods or methods of quadrature and curvature. The aim of the project work

> is [subjectwise] to give the student insight into the early history of the differential and integral calculus. Methodologically, the aim is to give the students a chance to work together in a group on a subject from the history of mathematics, to interpret primary sources, assess the secondary literature, chose important aspects, formulate a written report, and constructively criticize the work of another group.[17]

All objectives are formulated with respect to history (of mathematics). The overall goal is to provide students with historical knowledge about the development of mathematics and develop their historical awareness. The connections to subject matter of mathematics come about through reading of secondary literature (Katz's book), through analyses of sources and through the project work. The content matter of mathematics is subordinate to the content matter of history and historiographical issues. The overall impression is that the cultural argument lies underneath this implementation of history in the mathematics programme at Copenhagen University. The description of the objectives of the course is rounded off with the following declaration of expected outcome:

> Moreover the course will show connections between different mathematical fields that may appear unconnected in the more specialized mathematics courses. It will help students to formulate and form opinions about meta-mathematical questions and will counteract the tendency to absolutism that can result from ordinary text books. The students will see that during history there have been many different approaches to mathematics and they will meet cases where there are still different views about mathematical and meta-mathematical questions. That will ripen the student's view of mathematics.[18]

Historiographically, the ambition is to have a scholarly approach to history where historical episodes are interpreted on their own terms with an emphasis on differences between now and then. We also see indications of arguments in line with Beckmann's (2009) argument for interdisciplinary teaching as a way to counteract disciplinary narrow-mindedness and history as a method for revealing connections between mathematical fields that appear autonomous and disconnected in mathematics study programmes in universities. There is also a focus on the changing of meta-level rules. Philosophical issues are addressed in the course in connection with the historical development of mathematics, and we have here a clear interaction between history and philosophy.

26.4.2 Ex 2: Teaching with Original Historical Sources in Mathematics: New Mexico State University

The second example we have chosen comes from the developmental work that has been going on at New Mexico State University, USA, from the late 1980s spearheaded by the Professors David Pengelley and Reinhard Laubenbacher.[19] Their idea

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[17] http://sis.ku.dk/kurser/viskursus.aspx?knr=121117&sprog=2&forrige=57876

[18] http://sis.ku.dk/kurser/viskursus.aspx?knr=121117&sprog=2&forrige=57876

[19] http://sofia.nmsu.edu/~history/; http://www.cs.nmsu.edu/historical-projects

was to teach mathematics through primary historical sources. The group has developed and taught two undergraduate mathematics courses that are based on students' study of original sources from the history of mathematics. One of the courses is a lower division course in which students are introduced to 'great problems of mathematics'.[20] According to Laubenbacher and Pengelley (1992, p. 2), the course 'serves as an "Introduction to Mathematics" drawing good students to the subject [mathematics]'. The other course is called 'Great Theorems: The Art of Mathematics', and it functions as 'a capstone course for college juniors and seniors with substantial mathematics background' (Pengelley 2002, p. 1). A book for each course has been completed based on annotated original sources (Laubenbacher and Pengelley 1999; Knoebel et al. 2007). The courses (and the books) are centred around selected problems and theorems from different mathematical subjects. Each problem/theorem (chapter) comes with an extended introduction in which the authors present a chronicle of the problem/theorem often extending over several centuries.

Laubenbacher and Pengelley have presented the ideas behind their developmental work at conferences and in articles of which most can be found on their website 'Teaching with Original Sources in Mathematics'.[21] In contrast to what was the case at Copenhagen University, their aim is not to teach history of mathematics per se. Their aim is to teach mathematics through the use of mathematical sources from the past. Their work originated out of a critique of traditional undergraduate mathematics instruction in which they found a lack of motivation for abstract concepts and an approach in modern textbooks and typical instruction that 'deprives students of the sense that mathematics is a process … [and] … fail to illustrate the way mathematicians actually think about and work on problems' (Laubenbacher et al. 1994, p. 1). They wanted to remedy this by introducing a historical perspective in which the study of original sources is firmly integrated into 'all our courses, presenting these sources to motivate the modern theories they have spawned'. They provide two arguments for this:

> First, by reading original sources students are brought as close as possible to the experience of mathematical creation. … [Second], when students read original sources, they are initiated into the way mathematics is practiced. … Mathematicians at the cutting edge of their field don't read textbooks; they read research papers. (Laubenbacher et al. 1994, p. 2)

Hence, their argument for history in mathematics teaching at university level is pedagogical. Students should learn from the masters of the past.

In Jensen's terminology, we are dealing with the use of history that is guided by the idea that we can learn from history, i.e. a pragmatic use of history. The historical sources are subordinate to the mathematics. The selection and the reading of the sources are guided not by historical questions, but with respect to how central they are for the curriculum and their utility with respect to the learning of modern mathematics. Many of the exercises presented to the problems/theorems the courses are evolving around are mathematical questions aimed at understanding the modern theories.

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[20] http://sofia.nmsu.edu/~history/

[21] http://sofia.nmsu.edu/~history/

In the preface to their second book, they describe some of the benefits they have observed of using the past in this way as an approach to teaching mathematics. They write:

> Although teaching and learning with primary historical sources requires a commitment of study, the investment yields the rewards of a deeper understanding of the subject, an appreciation of its details, and a glimpse into the direction research has taken. (Knoebel et al. 2007, p. v)
>
> Primary sources also inject students directly into the process of mathematical research. They become active participants at the cutting edge of their own knowledge, experiencing actual research through grappling with the writings of great thinkers of the past. This creative immersion into the challenges of the past helps students better understand the problems of today. (Knoebel et al 2007, p. vi)

The main point is to learn mathematics, and history is used in the sense that the reading of the sources from the past is used as a pedagogical teaching method to teach students mathematics in an inquiry, research-like way. It can be argued that this approach to teaching has the potential to train, evoke and develop many of the eight mathematical competencies from Niss' conception of mathematics education. Historiographic and philosophical issues do not seem to play any significant role. In this respect, the courses differ fundamentally from the history of mathematics course taught at Copenhagen University. The selected sources also play very different roles in the two settings. In the booklet completed for the course in Copenhagen, the selection of the sources have been guided by historical and philosophical issues regarding the development and understanding of mathematics in the corresponding time period. The students are guided in their reading of the sources through questions that also point out how the mathematics of the past differs from our modern understanding and how the rules of the game have changed over time. In the courses developed at New Mexico State University, the selection of the sources has been guided by pedagogical principles (Barnett et al. 2011, p. 188). The sources play the role of authentic pieces of mathematics at research level for their time. They provide a context in which students can gain experiences with mathematical research processes. The students are guided in their reading of the sources through mathematical questions, and often they are asked to connect the mathematics of the source with the way it is presented in modern textbooks. The sources function as motivation for our modern theories and concepts.

Pengelley and his group have by now integrated their pedagogical approach of learning from the masters into many of the regular mathematics courses in the curriculum at New Mexico State University. This is done mostly in the form of modular projects.[22] Their goal is to allow students to learn all their mathematics in regular courses from primary sources. According to Pengelley, the 'team has now taught at least 3 of the regular dept. courses entirely from the projects we have developed, no more textbook'.[23] Some of these projects have also been implemented at Colorado State University (Barnett 2012).

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[22] See http://www.cs.nmsu.edu/historical-projects.

[23] Personal e-mail correspondence between David Pengelley and Tinne Hoff Kjeldsen on Monday the 25. of June, 2012.

26.4.3 Ex 3: Problem-Oriented Student-Directed Project Work: The RUC Model, Roskilde University

The last example of specific implementations of history (and philosophy) in mathematics education comes from the educational practice at Roskilde University in Denmark. Historical and philosophical perspectives on mathematics are implemented through problem-oriented, student-directed and group-organised project work. We have chosen to present three such projects. One of us (Tinne Hoff Kjeldsen) was supervising professor for two of the projects and was consulted as a supervisor by the group of students who completed the third project. The project works are exemplars of our own approach.

As will be explained below, the problem-oriented, student-directed and group-organised project work (the RUC model) as it is carried out at Roskilde University creates very complex learning situations for students. Hence, each project work has potential for multifaceted learning outcomes. However, in our presentation and discussion of the three projects, we have singled out in each of them one particular aspect of (possible) roles history and/or philosophy play in the mathematics education at Roskilde University.

All study programmes at Roskilde University are based on the four overarching pedagogical principles of problem orientation, student-directed project work, interdisciplinarity and exemplarity which constitute the RUC model (Salling Olesen and Højgaard Jensen 1999, pp. 16–17). In each semester the students participate in project work of their own choice. At the beginning of the semester, the students in a particular study programme form groups of 3–8 students in accordance with their interests.[24] They formulate a problem that they want to work on throughout the semester. A problem is eligible if it fulfils the requirements for the students' semester, e.g. in the mathematics programme each student participates in three projects, fulfilling three semester requirements: a 'modelling' requirement, a 'mathematics as a discipline' requirement and a 'profession'[25] requirement.[26] The justification for the project requirements is a mixture of the cultural argument, an argument for interdisciplinarity in its own right and as a vaccination against disciplinary narrow-mindedness, and arguments similar to those of the critical mathematics education: in the project work the students come to reflect upon and criticise mathematics in some of its forms of actions. In the project work, the students develop their three second-order competencies of overview and judgement from Niss' competence description of mathematics education presented above.

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[24] Three to eight students is the common group size, but students are allowed to perform a project on their own.

[25] Under the 'profession' requirement, the students have a choice between a modelling project, a pure mathematics project, a history and/or philosophy of mathematics project or a project on aspects of mathematics education, according to in what kind of direction, they want their future profession to move.

[26] See also Niss' (2001) narrative on his 25 years of experiences with the RUC model.

The projects where history and/or philosophy of mathematics enters are the ‘mathematics as a discipline’ projects and sometimes the profession projects. Before the students enter into the mathematics programme, they have completed a four semester interdisciplinary science programme (Blomhøj and Kjeldsen 2009). In this programme, the project requirement for the third semester is a ‘meta’ requirement, meaning that the students should work with a problem through which they will gain experiences with science as a cultural and social phenomenon. Of the three projects we discuss below, the first two are ‘mathematics as a discipline’ projects from the master’s programme whereas the third one is a ‘meta’ project performed in the 2-year interdisciplinary science programme (Kjeldsen and Blomhøj 2009). The projects are only constrained by these requirements. The problem a group of students chose to work on in a project should fulfil the requirements, and the project should meet the academic level to be expected of students who have reached the corresponding semester. There are no requirements on the content of the project work. The content is determined by the problem the students decide to work on. During the first 1–2 weeks of each semester, the students form groups based on their interests. Suggestions for problems will be raised, discussed and qualified in discussions between students and the professors who are going to be assigned as supervisors for the semester.

When the groups are formed, they will write an application to the board of study seeking approval of their problem and their project. They will also indicate which professor(s) they would like to have as a supervisor. The supervisor will follow the group throughout the entire semester. Normally, the group will meet with the supervisor once or twice a week for 1–2 h. The agenda of the meetings often comes from the students. They decide what they want to discuss, what they need help with and how they want to ‘use’ their supervisor. The supervisor makes sure that the academic standards are met and will let the students know if they are on a false track. In the RUC model, the project work can be thought of as student research projects. In each semester every student is part of a research team of fellow students, who perform a research project guided by the problem they chose to work on and by a supervising professor.

In the following we will present and discuss three specific student projects from the RUC model. As should be clear by now, the RUC project work creates a very complex studying and learning environment for the students. However, in the following we will focus, as mentioned above, on only one aspect of learning outcome for each project and leave the rest aside.

Project 1

Generalisations in the Theory of Integration: An Investigation of the Lebesgue Integral, the Radon Integral and the Perron Integral

This project was performed by two students. The students documented their work in a written report of 75 pages.[27] It originated out of a curiosity about different

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[27] The students’ project report can be downloaded at the following address: http://milne.ruc.dk/ImfufaTekster/pdf/403.pdf.

types of integrals. In the students' first analysis course, there was a footnote in the textbook that pointed out that there exists functions that are not Riemann integrable and that there are other types of integrals that can handle more functions than the Riemann integral, e.g. the Lebesgue integral. The two students wanted to investigate what these other types of integration can do. They immediately found out that the Lebesgue integral is just one of many different integrals. There is also the Denjoy, the Perron, the Henstock, the Radon, the Stieltjes and the Burkill integral, to mention just a few. The students noticed that they were often presented in the literature as generalisations of either the Riemann or the Lebesgue integral. These observations generated a bunch of questions (we are quoting from the students' project report): 'What do these integrals do? Why have so many types of integrals been developed? Why is it always the Lebesgue integral we hear about? What is meant by generalization in this respect? In what sense are the various integrals generalizations of former definitions of integrals? Are the generalizations of the same character?' (Timmermann and Uhre 2001, p. 1).[28]

In the end the students' project work was guided by the following problem:

> What were Lebesgue, Perron and Radon motivated by in their pursuit of their generalizations of the integral?
>
> What are the character and scope of the generalizations by Lebesgue, Perron and Radon, and what are the differences between them? (Timmermann and Uhre 2001, p. 3)

The students performed a historical study to answer the first part of their problem formulation. In Jensen's terminology, they had a scholarly approach to history. They studied a concrete episode from the history of mathematics from the perspective of the historical actors' motivation to extend and generalise the concept of the integral. The students read a selected variety of sources – Journal articles and books by Denjoy, Henstock, Lebesgue, Perron and Radon – with focus on the work of the last three mathematicians. For example, with respect to Lebesgue, the students read his note *Sur une généralisation de l'intégrale définie* which was published in *Comptes Rendus de l'Académie des Sciences de Paris* in 1901 and his thesis *Intégrale, Longueur, Aire* from 1902. They interpreted his motivation for the generalisation of the integral concept, as they explained in their report, 'detached from the context in which it is part of today and detached from our knowledge of the later significance of the concept' (Timmermann and Uhre 2001, p. 4).

As in the courses at New Mexico, the students studied the masters by reading research literature from a past episode in the history of mathematics, but in contrast to the courses at New Mexico, they were not guided by mathematical questions, but by historical questions. However, these questions were answered with reference to analyses of the mathematical content, theorems, definitions, proofs and techniques of the sources. In this way, the students gained first-hand experiences with processes and initiations of research in pure mathematics. With regard to mathematical competencies, an analysis of the students' work shows that six of the eight competencies

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[28] All quotes from student reports have been translated into English by us.

were invoked and trained during this project work, but the main purpose of their project was to develop their second-order competency of overview and judgement regarding the historical development of mathematics.

Project 2

Fourier and the Concept of a Function: The Transition from Euler's to Dirichlet's Concept of a Function

This project was designed and completed by four master students.[29] Their project work was guided by the following interest and curiosity:

> We wish to investigate the significance of Fourier for the development of the concept of a function. (Godiksen et al. 2003, p. 2)

The students analysed relevant sources from the works of Euler, Fourier and Dirichlet with respect to changes in as well as discussions about the concept of a function and the proper way to argue with functions. The relevance of the reading of sources from these three mathematicians was explained in the following way in the students' project report:

> The strength of focusing on these three mathematicians is, that it has given us the opportunity to study their original works (sometimes in translations) in depth, which have given us a more direct impression of their thoughts than secondary literature could have given us. (Godiksen et al. 2003, pp. 2–3)

We are again dealing with an ambition of employing a scholarly approach to history. The students wanted to interpret the past on its own terms. In their project report, they compared the works in the sources by Euler, Fourier and Dirichlet with each other and with our modern approach. They used the sources as 'interlocutors' emphasising the central ideas and the differences. With respect to Euler's concept of a function, the students' wrote in their report:

> The main elements of Euler's conception of a function could easily be explained very shortly, but that would not contribute to any deep understanding of the concept. In order to obtain this, one has to *look* at how Euler worked with functions. (Godiksen et al. 2003, p. 17; italic in the original)

In order to understand Euler's conception of a function, the students point out that it is necessary to study Euler's mathematical practice – how *he* worked on and used functions. The students gave the following interpretation of Euler's conception of a function:

> The definition of a function [Euler's definition] does not contain any specific information about its domain and image. This is because in Euler's theory, variable quantities are ascribed a property that render specifications of such sets superfluous. …
>
> … Euler conceived a variable as an arbitrary element, quite like our conception, but no constraints are allowed. The variable should be able to take all values … (it is universal). (Godiksen et al. 2003, p. 18)

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[29] The students' project report can be downloaded at the following address: http://milne.ruc.dk/ImfufaTekster/pdf/416.pdf.

Euler's analysis is global in nature – variables were universal, they were not limited in scope, and hence, Euler's functions had the property of analytic continuation. The students identified two meta-level rules of Euler's mathematical discourse: the generality of the variable and the general validity of analysis – two rules that were revealed and made into objects of the students' reflection through this historical project work, as can be seen from the following discussion in the students' report, where they wrote:

> This property which […] has been named the criteria of the *generality of the variable* clearly reflects the earlier mentioned paradigm of *the general validity of analysis*.
>
> […]
>
> Even though the use of the methods of analysis often created weird results the methods were used frequently in Euler's concept of a function. The reason why there weren't that many contradictions and paradoxes was that almost all Euler functions, which consists of analytical expressions, *have* all the above mentioned properties [they were nice], except maybe in isolated points. … Hence, there was no natural driving force that led to a clarification of the concepts of continuity, differentiability, and integration, since these properties so to speak were built into the concept of a function. (Godiksen et al. 2003, p. 22; italic in the original)

As pointed out by the students:

> Euler … was of the opinion that the analysis had to be developed such that it was able to describe all situations that occur in nature. (Godiksen et al. 2003, p. 23)

And in their treatment of Fourier's work, they continued:

> Fourier expresses clearly that mathematics is a tool for describing nature and mathematics had to be governed by nature. (Godiksen et al. 2003, p. 53)

The idea that mathematics has to be governed by nature is a third meta-level rule of past mathematical discourse that became exposed for the students and became an explicit object of reflection for them.

The students wrote a report of 88 pages explaining, analysing and interpreting the mathematics and the ideas about mathematics in the sources in order to answer their problem formulation. Again, it can be argued that six of the eight main mathematical competencies were invoked and trained during the project work together with the second-order competencies of history and philosophy. Here we have focused only on how this project work in history of mathematics functioned as a learning and teaching situation for students to experience meta-level rules in mathematics discourse and gain experiences with how these change over time (for further details, see Kjeldsen and Blomhøj (2012)). Within Sfard's theory of thinking as communicating, this project work is an example of how history of mathematics can function at the core of what it means to learn mathematics, as explained above.

Project 3

Rashevsky's Pride and Prejudice

The two projects discussed above relate to the two second-order competencies of history and the nature of mathematics. The project presented here on Nicolas Rashevsky's model for cell division from the 1930s relates to the third second-order competency of gaining knowledge about and experiences with actual applications of mathematics in other areas. In this case, it is the application of mathematics as a practice in other sciences. The project was conducted by four students. They read a paper by the physicist Nicolas Rashevsky (1934), where he discussed what he called *physico-mathematical aspects of cellular multiplication and development*. He presented the paper at a Cold Spring Harbor symposium on quantitative biology (see Keller (2002), and Abraham (2004)). His talk was followed by a discussion where the biologists in the audience were very critical of Rashevsky's approach in explaining cell division. Rashevsky's talk and the discussion were published from the proceedings of the meeting.

The students were curious about the hostile attitude of the biologists. They formulated the following problem that guided their project work:

> Why was Rashevsky unable to get through to the biologists of his time with his ideas? Was it because the biologists could not accept Rashevsky's scientific method? If so, was this then caused by a fundamental difference in biologists and physicists conception of biology and were/are controversies about the scientific method then a manifestation of this difference? (Andersen et al. 2003, p. 2)

The students studied the status of biology and of mathematics and physics in biology in the 1930s to understand the scientific culture of biologists and their conception of the significance of physics and mathematics in biology at the time. In reading Rashevsky's paper, the students became aware that he held a reductionist view of science. The students studied philosophy of biology and physics in order to understand whether the differences in opinion between the biologists and Rashevsky could be explained by differences in philosophical standpoints about science. Rashevsky's strategy was to take a general phenomenon that occurs in all cells and investigate its mathematical consequences. He chose cell metabolism. If, as he wrote in the paper, the process of division is found among such consequences, then cell division can be explained logically and mathematically as a direct consequence of the forces arising from cell metabolism.

In order to understand the critique raised by the biologists, the students had to read and understand Rashevsky's paper. It can be argued that in this process all eight mathematical competencies were invoked and trained. Regarding the second-order competency of gaining knowledge about actual applications of mathematics in other areas, the students experienced that the validity of arguments depends on the scientific context. For further details, see Kjeldsen (2010) and Kjeldsen and Blomhøj (2009). The students' historical and philosophical investigations in the project work contributed to critical mathematics education in the sense of Skovsmose, since the students came to reflect upon and criticise a form of action of mathematics, the action of mathematics in the production of knowledge in other scientific areas. For further details, see Kjeldsen and Blomhøj (2013).

The upper level undergraduate courses at Copenhagen University and New Mexico State University and the RUC model of project work at Roskilde University all address students who educationally wise are similar. However, the arguments, aims and objectives of the three different approaches of integrating history into the mathematics study programmes are, as we have seen, quite different. The project work in a sense combines the two approaches from Copenhagen and New Mexico. The problem, the students work on in the RUC model, is a so-called metaproblem. It is a problem *about* mathematics, historical and sometimes also philosophical, but the students' domain of inquiry is the mathematics of the past. In order to answer their problem formulation, the students work as historians (and philosophers) with historical (philosophical) problems. To get answers, they dig into the sources, studying and interpreting the mathematics – though not from a modern perspective, as is the case in the New Mexico approach, but from the historical actors' perspective within their mathematical practice.

26.5 Examples of Philosophy in University Mathematics Programmes

26.5.1 Philosophy of Science in University Education in Denmark: Aims

In 2000 the Danish Government and the Association of Vice-chancellors of Danish Universities decided to reintroduce a philosophy course for all university students.[30] This new course is called 'Fagets videnskabsteori' which translates to 'philosophy of science of the subject of study'. The overall aim of this course is to qualify students' specialisation in their subject by allowing them to see it from a broader and more general perspective. Ten specific points were listed as requirements; see http://www.nbi.dk/~natphil/FVT/i_Alment.html. We mention in particular 3 and 4 that address the particular implementation of these courses, requiring (i) that the courses should be research based and (ii) that the curriculum should 'take interesting questions from the field of study and combine them with questions of a more general kind'.

The overall aim was to address the question of how knowledge is tackled in a knowledge society. A university graduate should not only know narrowly his/her own subject but should also obtain competencies within values and perspectives and be able to reflect. These aims are elaborated on by Professor Hans Fink, who was one of the researchers involved in the discussions prior to the Bill (Fink 2001). He states that the overall aim is to produce better students and to prepare them for the job market. He says:

> We thought that a course that allows the students to reflect on their subject's distinctive philosophical character, seen in a wider, general, philosophical, and historical context,[31] would be well-founded, if it could forestall the risk that the students' professional absorption

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[30] Until 1971 it was compulsory for all university students in Denmark to take an introductory philosophy course, so-called filosofikum. This course was mainly handled by philosophers.

[31] In addition 'videnskabsteori' is mentioned. It is best translated as 'theory of science' and is usually thought of more broadly than philosophy of science, including social science, history of science and ethics.

> leads to narrow-mindedness that makes them less fit to engage with the interdisciplinary connections that they will later have to deal with. A course like this will also counter the often criticised schoolification of the universities by encouraging the students to systematic reflection about what a university, science and research actually are. … Finally, the course could fulfil a large need of society, if it could ensure that everyone with a university degree is given the opportunity to make clear the social and ethical responsibility of both science and the individual researcher.

It is thus clear that the aims of this course are broad. One major requirement, however, is that all these reflections take as a starting point the actual subject. The course – in mathematics – should therefore:

1. Include philosophical reflections relevant to the subject in question, i.e. mathematics.
2. Place the subject in a wider context, e.g. discuss mathematics' distinctiveness in relation to other subjects.
3. Discuss the role of mathematics, research and universities in society.
4. Discuss ethical questions relevant to the subject.

Overall the stress is on the students' abilities to *reflect* and *critically examine ideas*. These are philosophical competencies, so the core of the course is a philosophical one. This means in particular that the course should not dictate any one perspective as the right perspective, but should aim at giving the students tools to handle these competencies. In what follows we present examples of how this course is implemented.

26.5.2 Implementation of Philosophy of Science Course in Aarhus University and University of Southern Denmark

In what follows we give concrete examples of how this course is handled at the Universities of Aarhus (AU) and Southern Denmark (USD). The overall structure of both courses is the same. Both courses' credit is 5 ECTS. They include common lectures, presentations by students, discussions and group projects, and they address the above-mentioned points. Many of the included topics are the same. But there are differences in how these are presented. We present Aarhus first, since the Centre for Science Studies at Aarhus University has devoted much time to develop a 'philosophy' on how to handle courses on the philosophy of natural science. In a recent paper Kragh Sørensen writes:

> We have adopted a teaching philosophy of using historical and contemporary case studies to anchor broader philosophical discussions in the particular subject discipline under consideration. Thus, the courses are tailored to the interests of the students of the particular programme whilst aiming for broader and important philosophical themes as well as addressing the specific mandated requirements to integrate philosophy, some introductory ethics, and some institutional history. These are multiple and diverse purposes which cannot be met except by compromise. (Kragh Sørensen 2012, p. 1)

The course starts by addressing the question ‘what is mathematics?’ and includes topics like the application of mathematics, discussing the question concerning ‘The Unreasonable Effectiveness of Mathematics in the Natural Sciences’ (Wigner 1960) and issues concerning modelling, the role of proofs and the foundation of mathematics and the role of mathematics and university in society, including mathematics and gender and ethical issues. To give a better sense of how this philosophy works in practice, we present two examples in more detail. One concerns the role of proof in mathematics, the other, the (unreasonable effectiveness of the) applications of mathematics.

Example 1

When dealing with the role of proofs, the course takes as a starting point a general held belief, presumably also among the students. A proof is taken to be[32]:

- Axiomatic deductive, obtained from accepted assumptions
- Employing logical steps in a specified logical system
- (In principal) fully formalised (or possible to formalise)

For homework the students are asked to consider the following questions:

- What is the difference between foundation and practice?
- What is the difference between formal and rigorous proofs?
- What is the foundation, and how certain is it?
- Can proofs prove or can they (at most) convince?

The aim of the treatment of this topic is to ‘enable discussions about proofs that go beyond the idea that proofs merely guarantee truth’. In addition, the teacher ‘wishes to emphasise the role of proofs as tools of communication in a mathematical discourse’ (personal communication).

The first case study to challenge the standard conception of proof is Perelman’s proof of the Poincaré assumption. This case shows, among other things, that the mathematical community may disagree on whether a presented proof is actually a proof. It also illustrates different motives for pursuing a mathematical career – fame, glory and money – or the pleasure of obtaining insight. Later the course considers the role of proof in more detail. In order to discuss this theme, for example, Wiles’ proof of Fermat’s last theorem is presented. This case challenges the standard conception of proof. For one thing, the proof is too long and too complicated for the average mathematician to follow it through. This leads to a discussion about how one trusts a given proof and which criteria should hold for a ‘good proof’. The discussion brings in many examples from current mathematical practice. The phenomena of experimental mathematics (and use of computers in mathematical proofs in general) are treated in order to discuss, for example, the notion that mathematical proofs and knowledge are a priori.

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[32] The following is taken – and translated – from slides used in the course.

Example 2

Questions pertaining to the conception and role of a proof could be taken to be internal to mathematics. In contrast are questions concerning the relation between mathematics and reality. One question that has puzzled philosophers and scientists concerns 'The Unreasonable Effectiveness of Mathematics in the Natural Sciences' (Wigner 1960). It is clear that mathematics is applied to the real world. Since the modern development of mathematics, however, it has been a challenge to explain actually why and how mathematics can be applied. The answers – and the degree of mystery involved – depend on which view of mathematics is taken. Wigner presents a view of mathematics, where concepts are developed with no connections to considerations of the world but in order to develop beautiful and interesting theorems. On this view, it is clearly a mystery that mathematics can say anything about the physical world. Several solutions to this problem have been offered; see, for example, Grattan-Guinness (2008). The course in Aarhus introduces this question and indicates how proponents of different views would account for the applicability (Platonism, Formalism, Kant, Empiricism). In addition, some case studies are introduced in order to qualify the discussion. One example illustrates interrelation between development of mathematics and – in this case – chemistry. It tells part of the story on the development of crystallography. In this theory crystals are modelled as certain lattices with symmetry properties (translation and rotation). According to the main theorem of crystallography, crystals can only have certain types of symmetries. In 1984, however, a crystal was found contradicting this result. This led to the notion of a quasicrystal and an ongoing search for a mathematical theory describing these.

The course also stresses the point made by several mathematicians (Hilbert 1902; Poulsen 2001, and Toft 2001) that mathematics solves *problems*. Problems can be either internal mathematical problems or external problems.

An important part of this topic is 'to point out and discuss the difference between a mathematical model and the part of reality that it is supposed to be a model of. In this lies also the task to point out the choices (perhaps even theory-laden) made when formulating the model, and the relations one could (wrongly) think there is between a model and reality. This leads to the possibility of discussing predictions made from mathematics and mathematical explanations in natural science' (personal communication with Kragh Sørensen). Mathematical models are widely used in today's society and for many different purposes. In some uses, models are tools to solve problems. As such, they can be very simple or extremely complicated giving rise to a whole range of problems.[33] Mathematical models are also used in arguments. When used in this way, it is important to be aware of the fact that a model can at most tell something about the actual data or assumptions put into the model. If the model is complex, meaning that the resulting mathematical problem cannot be solved by exact methods, it may not even give certain results about these. Even so, mathematical models are

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[33] The topic of the role of models in society is also dealt with at USD, and the following description is mainly based on the treatment there.

often used in, for example, political debates, where the certainty of mathematics (faultily) is attributed to the model (see Kjeldsen 2011b). When teaching this topic, the students are shown traditional steps of a modelling process and are asked to think these through for various examples. In addition they find examples of models used in society, discussing which roles they play and – if possible – which assumptions have been made when formulating the model.

Overall, the philosophy of allowing examples to generate the philosophical discussion seems to work. In order to generate and qualify the discussion, however, certain philosophical theories and notions need to be explained as the course moves along. It is also the case that certain convictions the students (may) hold need to be explicitly stated before they are discussed as was the case in the first example, where the standard conception of proof is discussed. This is not surprising, since we are dealing with mathematics students, not philosophers. It takes training to think philosophically, i.e. to be able to pose the relevant questions or to pose questions at all and to learn to use tools to handle these questions.

26.5.3 Example from University of Southern Denmark

In contrast, the course in Odense takes as a starting point certain *philosophical questions* and tries to answer these based on actual examples of mathematics. When entering the mathematics programme at USD, a student will take courses within natural science during the first year – together with all students who wish to study natural science. The philosophy behind this is to strengthen the interdisciplinarity of subjects within natural science. This philosophy carries through to the course in the philosophy of science, where there is a common core and the lectures are held for all students. The course also consists of a subject-based part so that, for example, mathematics students have a number of classes that addresses issues particularly relevant for mathematics. In the common part, it is possible to address general themes such as the distinctiveness of natural science and mathematics, ethics and the role of research and university in society. We also treat ‘standard’ schools in philosophy of science, such as inductivism, Popper’s critical rationalism and Kuhn’s paradigms and revolutions. The point here is not so much to discuss these from a philosophical point of view, rather it is to see which questions they raise and how they propose to answer them. The main idea is to consider these questions and answers in the light of their subject. As a supplement, the students are presented a number of case studies, illustrating and challenging conceptions of science. These examples range from the overthrow of the Phlogiston theory to discussions concerning Creationism and Intelligent Design and the status of research in particle physics.

In Danish, the word for science is ‘videnskab’. It includes ‘viden’ which means knowledge and infers that it is a practice that yields knowledge. Students are given the philosophical definition of knowledge as ‘justified true belief’ and are encouraged throughout the course to reflect on whether the methods used in their discipline do in fact yield knowledge in this sense. It is also stressed many times during the course that it poses questions and provides *possible* answers and their job is to reflect on these answers, finding their own.

Example 3

The final example concerns the question about the nature of mathematical objects. In the lecture, the students are introduced to the realism-antirealism debate in the philosophy of science. One point is that even in natural science – that supposedly should concern the real world – there are questions to ponder about. For a first example, take the phlogiston theory that during part of the eighteenth century was held to explain processes of combustion. This theory was overthrown by Lavoisier's theory stating that oxygen is the fundamental matter at play in such processes. The question is whether our theories today could suffer the same fate or our current scientific theories are better? If they answer yes to this last question, the challenge is to argue just *how* these theories are better and even explain what a 'better' theory means. Most scientists' intuitions will tell them that there is progress in the development of scientific theories. The challenge is to explain in which sense. A more recent example concerns the theory of dark matter and energy. So far we (the scientists) only have circumstantial evidence that these types of 'objects' exist. Scientists have never seen (it cannot be observed, since it does not radiate electromagnetic force) or isolated samples of dark matter. Even so, they are convinced it exists (see Sannino 2009). This raises the challenge to formulate rational criteria to determine whether something exists. Within philosophy of mathematics is the dispute on whether mathematical objects exist independently of human beings, in case one is a realist – or Platonist – or whether they do not, in which case one is an antirealist. The way this question is tackled is to present the students with:

- A number of different versions of realist and antirealist positions. Pointing out that there are many possibilities for being of each kind.[34]
- Equally important, the motivation for and arguments typically given in favour both of realism and antirealism. Realists would, for example, argue that mathematical propositions are true, and then it follows from a correspondence theory of truth that mathematical objects exist. An influential argument which dates back to Frege but is usually credited to Quine is the indispensability argument (Colyvan 2001; Shapiro 2000). It combines the fact that mathematics is indispensable to natural science with a confirmational holism[35] and an ontological commitment to entities of any accepted theory. Anti-realists in turn argue (with Benacerraf 1973) that the existence of abstract mathematical objects outside of space and time makes it a mystery of how we obtain knowledge in mathematics.

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[34] Maddy's (1990) set theoretic realism and Shapiro's (2000) ante rem structuralism are examples of what is presented. In addition we discuss Field's (1980) fictionalism and the empiricism of Mill.

[35] A scientific theory is confirmed as a whole. If mathematics is part of a confirmed scientific theory, then the included mathematics is also confirmed.

> A popular strand of anti-realism is fictionalism, denying that mathematical statements are true (else realism follows) rather they are a certain kind of fictitious statements.

Based on these positions, arguments and motivations, the students are asked to determine for themselves which kind of position they find most convincing. When doing this they are, of course, asked to take into account their own experience with mathematics. Taking any one position also requires producing arguments for this position and in some cases countering the arguments of the other side. As an example, one could question the statement that mathematical sentences are true in the same sense as ordinary sentences or that mathematical theories are confirmed alongside scientific theories.

In addition we have responsibility to show students the many sides of mathematics that they do not encounter in their traditional lectures. They are most often taught from textbooks.[36] These are re-presentations of the mathematical theories, definitions, theorems and proofs as presented in research articles, presented in a form that intends making it accessible for the student. In this form, however, the original presentation and motivation is often lost. What else is missing is the, often long, process leading to the results in question.

26.5.4 Are the Aims Fulfilled?

The examples given mainly address aim number 1, i.e. introducing students to philosophical questions to their subject. We hope to have conveyed in the above presentation that we aim at the following:

1. Making the students aware of some of the philosophical questions underpinning their subject.
2. Providing them with tools to tackle these questions, by teaching them a certain terminology, positions and ways of thinking distinct to philosophy.
3. An emphasis on the fact that they are mathematicians, so that their expertise when dealing with such questions lies in the ability to critically examine mathematical assumptions and point to misconceptions about mathematics.
4. It is also our task to show our students a variety of examples enabling them to fulfil 3.

These aims are in part achieved. In general, however, we find that students are not particularly motivated to take the courses in philosophy of science. It is our impression, though, that most students appreciate the course more after finding out what it is actually about. As we were about to write this chapter, the second author of the present chapter asked students from her last class about their thoughts

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[36] In Aarhus and Copenhagen, it is very common for teachers to write their own textbook material.

concerning the relevance of such a course. One student complains that he/she does not find it relevant now, but still concludes that it might later lead to some reflections. Among the positive responses, a student found the course relevant, because it teaches them to think differently. Answers like this are particularly welcome!

We recall the three types of second-order competencies. The first competency addresses applications of mathematics whereas the other two concerned the historical development of mathematics as well as its nature. It is clear that the courses in philosophy of mathematics described above intend to provide students with competencies in order to deal with both the problems concerning various applications of mathematics as well as fundamental questions regarding mathematics. More specifically, we find that one major role (on the mathematical level) these courses play is to present *a wider picture of mathematics* than is usually given in regular mathematics courses. Students are shown that mathematics is more than 'definition-theorem-proof' – a picture objected to by the Fields medallist Thurston (1994). The intention is to get them behind the scenes of doing mathematics. A related role is to enable and convince mathematics students to become ambassadors of mathematics. For one thing, they, if no one else, should be able to say something about what mathematics is, its distinctiveness and importance (mathematics is actually used everywhere in our society), and that mathematics need not be frightening.

Students ought to also be aware of some of the ethical problems concerning application of mathematics – or applications in general – and have some tools to handle these.

Finally, the course may even help them on a personal level in their mathematical studies. Philosophy as well as mathematics seeks *arguments*. Training to argue within philosophy strengthens ability to argue correctly in mathematical reasoning.

26.6 Conclusion

Comparing the identified roles of the courses in history and philosophy of mathematics, we find that they (to a large extent) coincide. On the mathematical level, one motivation for both history and philosophy is to provide students with a wider picture of mathematics, in particular to include meta- mathematical considerations 'preventing the absolutist tendency of mathematics textbooks'. On a social, or cultural, level is the motivation of interdisciplinarity counteracting disciplinary narrow-mindedness (Beckmann 2009; Fink 2001). In addition is a responsibility to show the political and social roles of mathematics, which can be done by both history and philosophy. On a personal level it is argued that including historical and philosophical perspectives make the students better mathematicians. We have even seen that both perspectives can be used to strengthen their abilities in mathematics. Philosophy of mathematics does this, for example, by teaching them to argue.

Although history and philosophy are quite different (history analyses and interprets sources and searches for explanations for historical processes of change – philosophy poses questions, critically examines ideas and provides arguments), they do interact in fundamental ways. In the history courses, most notably in the group projects, the motivations for doing the historical studies were in some cases philosophical. For example, the question concerning different types of generality, posed by the first group, is a philosophical question. Similarly, the aims of the philosophy courses could not be fulfilled without a handful of good (historical) cases to show to the students.

One remaining challenge is to convince students that courses like these are important for their mathematical training. It is also an open question whether the students actually benefit and use tools obtained from these courses in their professional careers.

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Chapter 27
On the Use of Primary Sources in the Teaching and Learning of Mathematics

Uffe Thomas Jankvist

27.1 Introduction

Why would one go to the extent of using a, possibly very old and maybe even somewhat inaccessible, primary original source[1] in the teaching and learning of mathematics, when so many contemporary textbooks are ready-made and pedagogically prepared for dealing with the same mathematical topics using modern-day language, coherent notation, etc.?

The above question is the overall one to be addressed in this chapter. The question is, of course, not a new one. It is a question which has already been addressed on several occasions and by various researchers of mathematics, the history of mathematics, and of course mathematics education, notably in the ICMI[2] Study on *History in Mathematics Education* (Fauvel and van Maanen 2000), where Jahnke, Arcavi, Barbin, Bekken, Furinghetti, El Idrissi, Silva da Silva, and Weeks, in the chapter on *The use of original sources in the mathematics classroom,* state:

> Among the various possible activities by which historical aspects might be integrated into the teaching of mathematics, the study of an original source is the most demanding and the most time consuming. In many cases a source requires a detailed and deep understanding of the time when it was written and of the general context of ideas; language becomes important in ways which are completely new compared with usual practices of mathematics teaching. Thus, reading a source is an especially ambitious enterprise, but […] rewarding and substantially deepening the mathematical understanding. (Jahnke et al. 2000, p. 291)

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[1] Throughout the chapter the phrases "primary original sources," "primary sources," and "original sources" are used interchangeably but always to mean the same.

[2] ICMI is *International Commission on Mathematical Instruction*.

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This chapter addresses some of the reasons usually given for resorting to primary original sources in the teaching and learning of mathematics as well as exemplifies some of the approaches to doing so. At the end of the chapter, the use of original sources as a potential way of dealing with certain problems and issues in mathematics education in general is discussed, i.e., problems not only related to the teaching and learning of mathematics itself. Some illustrative examples on the use of original sources, and (empirical) didactic findings in relation to such, will be given later in the chapter. But before we get to that point, a bit of background information seems in order.

27.2 The Background and Academic Forums of Using Primary Original Sources

As mentioned, the discussion of using primary original sources in the teaching and learning of mathematics is not a new one. Historically speaking, it was the French, whom with the Commission Inter-IREM[3] first dealt with the use of original sources in a more productive manner and developed a wide range of related activities (see, e.g., Jahnke et al. 2000).[4] In the English-speaking part of the world, the HIMED movement[5] in England, initiated by John Fauvel, made several contributions, and so did the IHMT[6] initiative in the USA, one result being the massive collective work *Historical Modules for the Teaching and Learning of Mathematics,* edited by Katz and Michalowicz (2004). Traditionally, the discussion of using original sources is one which is embedded in the larger discussion of generally using history of mathematics in mathematics education (cf. Chap. 21 by Michael Fried). For that reason, much of the literature on using original sources is to be found within the literature on using history.[7] Still to this date, the most comprehensive volume available on the topic is the aforementioned ICMI Study (Fauvel and van Maanen 2000), which provides an account of the literature available up until the year 2000 as well as extensive examples on the use of history and original sources. The purpose of this chapter is therefore not to repeat what has already been done and said in the ICMI

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[3] IREM is *Institut de Recherche sur l'Ensignement des Mathématiques*. Inter-IREM here refers to the particular Inter-IREM Commission on history and epistemology of mathematics under the coordination and leadership of Evelyne Barbin.

[4] Of course, smaller-scale initiatives had been taken in other places. As an example, the pioneering work of Abraham Arcavi from Israel is mentioned, beginning with his Ph.D. (Arcavi 1985) and the subsequent extensive publications in several journals.

[5] HIMED is *History in Mathematics Education*.

[6] IHMT stands for *Institute in the History of Mathematics and its use in Teaching*.

[7] A few examples of collections published before year 2000 including discussions of the use of original sources are Calinger (1996), Katz (2000), Laubenbacher and Pengelley (1999), and Swetz et al. (1995).

Study and its chapter on original sources,[8] but instead to provide a slightly different perspective on the use of original sources and refer to some of the more recent developments on this topic.

As a brief overview of literature in general on the use of original sources after the year 2000, the following account is offered: In 2002, a conference was held in Kristiansand as a tribute to John Fauvel who passed away one year earlier and also as a celebration of the bicentennial year of the birth of Niels Henrik Abel – *the Abel-Fauvel Conference* – the proceedings of which was published in the book *Study the Masters,* edited by Bekken and Mosvold (2003). Besides offering various contributions related to the history of mathematics, this book also offers some papers on the use of original sources in the classroom.[9] The Abel-Fauvel Conference was a Nordic preconference to ICME[10] 10 and the HPM[11] satellite conference of 2004. In the proceedings of HPM2004, which were edited by Furinghetti et al. (2007), there are also some contributions of interest, not least the report from a panel discussion coordinated by Barbin on original sources in the classroom. The HPM2004 was a joint meeting with the ESU4,[12] since their quadrennial and triennial conferences coincided in 2004. The proceedings from ESU5 edited by Barbin et al. (2008) also offer various input on the debate of original sources and do so in relation to various educational levels and teacher training.[13] The same goes for the proceedings from ESU6, edited by Barbin et al. (2011), from which special attention should be given to the plenary talk by Glaubitz (2011), which empirically compares some of the approaches for using original sources to be discussed later in this chapter. In fact, this plenary is the first entry in an entire section devoted to the use of original sources in the classroom and their educational effects.[14] At ICME there is a Topic Study Group (TSG) on *The role of history of mathematics in mathematics education*. Another recent initiative in relation to history, and therefore also original

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[8] It should be mentioned that Chap. 9 in the ICMI Study is not the only one which addresses elements of using original sources, so do also Chap. 5 (in particular Sect. 5.3 in this), Chap. 7 (e.g., Sect. 7.3 which addresses matters of the genetic approach), and Chap. 8 in which many of the outlined examples rely on original sources.

[9] For example, those of Furinghetti and Somaglia, Horng, Pengelley, and Siegmund-Schultze.

[10] ICME stands for *International Congress on Mathematical Education*, the quadrennial world congress of ICMI, which took place in Copenhagen in 2004, and since in Monterrey, Mexico, in 2008 and in Seoul in 2012.

[11] HPM stands for ICMI-affiliated *International Study Group on the Relations between the History and Pedagogy of Mathematics,* which has its quadrennial international meeting at the time of ICME but also has yearly local meetings as, for example, those of the *HPM Americas*. The HPM satellite conference was in Uppsala in 2004 and since then in Mexico City in 2008 and in Daejeon in 2012.

[12] ESU stands for *European Summer University on History and Epistemology in Mathematics Education*, which is an initiative of the French IREM. ESU5 was in Prague in 2007; ESU6 is Vienna in 2010; and ESU7 is planned for Barcelona in 2014 and will now be held every fourth year so that it no longer coincides with HPM satellite meetings.

[13] Some examples are the contributions by Bastos and Veloso, Fried and Bernard, Glaubitz, Guichard, Katz, Poulos, Thomaidis and Tzanakis, and Weeks.

[14] Other contributions related to the use of original sources also occur outside this section of course, e.g., those by Kjeldsen, Rosas and Pardo, and others.

sources, is the working group on *History in Mathematics Education* at CERME.[15] The volume recently published in MAA Notes on *Recent developments on introducing a historical dimension in mathematics education*, edited by Katz and Tzanakis (2011), includes papers originally presented at the ICME11 TSG on history, HPM2008, and CERME6.[16] *From Calculus to Computers: Using the Last 200 Years of Mathematics History in the Classroom*, edited by Shell-Gellasch and Jardine (2005),[17] is yet a book which was published in the MAA Notes after the ICMI Study from 2000. Another stand-alone publication which is clearly of relevance for the use of original sources in the teaching and learning of mathematics is the collection of projects relying on primary historical sources by Knoebel et al. (2007). In 2007 a special issue of *Educational Studies in Mathematics* entitled "The history of mathematics in mathematics education: theory and practice" was edited by Furinghetti, Radford, and Katz. This issue includes several articles relevant for the topic of using original sources.[18]

In relation to the use of original sources, the Oberwolfach meeting organized by Furinghetti et al. (2006) must also be mentioned. One of the outcomes of this meeting was the formulation of a set of questions to guide future research on the use of original sources:

1. What are the possible epistemological/theoretical basis and frameworks for research and development towards the integration of original sources into the teaching and learning of mathematics?
2. What are the characteristics of viable models for implementing the integration of original sources in the teaching and learning of mathematics?
3. What is the actual impact of these models on students' and teachers' learning and understanding of mathematics, and on teachers' teaching practices?
4. How can historical research and practice inspire, impact, support or supply explanatory frameworks and working tools for research on learning and teaching mathematics?
5. How can research and practice in mathematics education inspire, support and broaden the research in the history of mathematics in general, and on original sources in particular? (Furinghetti et al. 2006, p. 1287)

As the last thing, the recent conference in Paris in honor of Michèle Artigue – *Colloque Artigue 2012* – is mentioned, where a workshop on epistemology – *Atelier 5: epistémologie et didactique* – was organized by de Hosson, Chorlay, and

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[15] CERME is *Congress of European Research in Mathematics Education*, which is held every second year in between HPMs and ESUs. The WG on history was at CERME6 in Lyon, 2009; CERME7 in Rzeszów, 2011; and CERME8 in Antalya, 2013.

[16] The most important chapters in this volume in relation to original sources are those by Barbin (Chap. 2), Kjeldsen (Chap. 15), and Pengelley and colleagues (Chaps. 1 and 17); but other chapters are clearly also relevant.

[17] Examples of contributions discussing the use of original sources in this collection are Atzema and White, D'Antonio, Pengelley, and Rogers.

[18] In particular the articles by Arcavi and Isoda (2007), Barbin (2007), Katz (2007), and Thomaidis and Tzanakis (2007)

Jankvist. The first session of this workshop was devoted to young researchers accounting for the epistemological (and historical) dimension in their doctoral theses.[19] Often, it is the case that French doctoral students begin their doctoral work with an epistemological/historical account of the mathematical concepts which their thesis addresses, and in this work the study of original sources play an essential part, for example, in identifying epistemological obstacles (e.g., Bachelard 1938; Brousseau 1997). To end this section where it began, namely, with the French Inter-IREM Commission on history and epistemology of mathematics, Evelyne Barbin, who was invited to speak in the second session of this workshop, pointed out that in the IREM context around 1994 epistemology also functioned as a "weapon" against the widespread view of mathematics as a language, since epistemology puts emphasis on mathematics as an activity.[20]

It is now time to introduce some general constructs developed in the setting of history in mathematics education – constructs, which will prove themselves useful in our further discussion of primary original sources.

27.3 A Distinction Between In-Issues and Meta-issues of Mathematics

In the context of using history – and thus also original sources – in mathematics education, we may distinguish between the inner issues of mathematics and the metaperspective issues (Jankvist 2009a). When history is used as a *tool* for teaching and learning of mathematics,[21] the primary focus is on the inner issues – or *in-issues* – of mathematics such as mathematical ideas, concepts, theories, methods, algorithms, and ways of argumentation and proof. When history is used more in terms of a *goal*,[22] the focus is on the metaperspective issues – or *meta-issues* – of mathematics as a scientific discipline, regarding it as a goal to show the students something about how mathematics has come into being, its historical development, human and cultural aspects of this development, its interplay

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[19] The presenters were Thomas Barrier, Patricia Crépin, Mathias Front, Eric Laguerre, and Caroline Poisard. Furthermore, posters on the role of epistemology and history, also in relation to original sources, were presented.

[20] Currently, *Science & Education* is preparing a special issue on "History and Philosophy of Mathematics in Mathematics Education," guest edited by Victor J. Katz, Uffe Thomas Jankvist, Michael N. Fried, and Stuart Rowlands. This issue will include new articles discussing the use of primary original sources in mathematics education.

[21] The history-as-a-tool arguments may be subcategorized into being concerned with history as a motivational and/or affective tool, history as a cognitive tool (e.g., the idea of epistemological obstacles), and the role of history in what may be referred to as the evolutionary arguments (the recapitulation argument or historical parallelism) (Jankvist 2009a).

[22] Note that this is not the same as teaching the history of mathematics *per se*.

with society through applications, or issues of epistemology, ontology, etc.[23] For example, learning about the number sets (N, Z, Q, R, C), their interrelations, their cardinalities, etc., is considered to be a study of in-issues. On the other hand, learning about the historical development of the different kinds of numbers, the difficulties regarding the acceptance of the irrational numbers, the negative numbers, or the complex numbers concerns aspects of the meta-issues of mathematics.

Because the distinction between in-issues and meta-issues applies not only to the use of history in mathematics education but also to the use of philosophy and actual applications of mathematics (Jankvist 2013), it will be relevant for the use of original sources in any of these contexts as well. As further examples of various meta-issues to be addressed from the point of view of history, application, and philosophy of mathematics in mathematics education, we may consider:

> How does mathematics evolve over time? What forces and mechanisms can be present in the evolution? Do society and cultural circumstances play a part in this evolution? If so, how? And does mathematics then depend on culture and society, place and time? Is old mathematics also obsolete mathematics? (Niss 2001a, p. 10, my translation from Danish)

> Who, outside mathematics itself, actually uses it for anything? What for? Why? How? By what means? On what conditions? With what consequences? What is required to be able to use it? Etc. (Niss and Højgaard 2011, p. 74)

> What is characteristic of mathematical problem formulation, thought, and methods? What types of results are produced and what are they used for? What science-philosophical status does its concepts and results have? How is mathematics constructed? What is its connection to other disciplines? In what ways does it distinguish itself scientifically from other disciplines? Etc. (Niss and Højgaard 2011, pp. 75–76)

The distinction between in-issues and meta-issues bears some resemblance to that of Davis and Hersh (1981), who talk about the "inner issues" and the "outer issues" of mathematics, or that of Niss (2001b), who talks about "knowledge of mathematics from the inside" and "knowledge of mathematics from the outside."

Even though a use of history (or application or philosophy) as a tool is concerned with students' learning of mathematical in-issues, this is of course not to say that meta-issues cannot act as a means (tool), for example, by motivating students, to reach an end (goal) of learning specific in-issues. In a similar manner, when concerned with history (or application or philosophy) as a goal, it is clear that certain meta-issues cannot be understood without comprehension of some mathematical in-issues (see Jankvist 2011 for examples). The distinction between in-issues and meta-issues is merely a useful way to talk about the primary foci of including history (or application or philosophy) and thus also of resorting to primary original sources when doing so.

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[23] For a further discussion of history as a tool and history as a goal, see also Tzanakis and Thomaidis (2012).

27.4 Various Reasons for Using Primary Original Sources

In this section we take a look at some of the reasons usually given for using original sources in the teaching and learning of mathematics, relying on the distinction between in-issues and meta-issues. To illustrate how this notion may be applied to uncover some of the underlying motives for resorting to original sources, let us have a look at the following list of reasons provided by Pengelley, one of the pioneers of using original sources at US undergraduate level:

> [1] … motivation and deep connection along time, [2] understanding essence, origin, and discovery, [3] mathematics as humanistic endeavor; [4] practice moving from verbal to modern mathematical descriptions; [5] reflections on present day status and paradigms; [6] participating in the process of doing mathematics through experiment, conjecture, proof, generalization, publication and discussion; [7] more profound technical comprehension from initial simplicity; [8] also dépaysement (disorientation, cognitive dissonance, multiple points of view); [9] and a question-based curriculum that knows where it came from and where it might be going. Questions before answers, not answers before questions that have not been asked. (Pengelley 2011, p. 3, numbering not in original)

Clearly, reason 9 refers to the commonly seen structure of modern mathematics textbooks, where definitions and theorems are usually presented first, and then, motivation and application follow afterwards. As the reader will know, the historical development of mathematical theories, concepts, etc. often is the exact opposite; one is motivated by a problem or an application, the solution of which leads to theorems, proofs, and in the end definitions.

Pengelley's other eight reasons for using primary original sources may be ordered according to their focus being either on the in-issues or the meta-issues of mathematics. Reason 3 about "mathematics as a humanistic endeavor" and the part of reason 2 which reads "understanding origin and discovery" are mainly concerned with the meta-issues. Reasons 4, 6, and 7 on "practice moving from verbal to modern mathematical descriptions" and "participating in the process of doing mathematics…" and "more profound technical comprehension…" concern in-issues in one way or another. Of course, these reasons or arguments are subject to interpretation. This is the case for the part of reason 2 which reads "understanding essence"; does this refer to in-issue mathematical essence of a given concept or topic or does it, for example, refer to the meta-issue applicational essence of the concept in an extra-mathematical context? And similarly, does reason 5 about "reflections on present day status and paradigms" refer to, for example, inner mathematical concerns of unsolved problems, unproven conjectures, etc. or to aspects of a more metaperspective nature regarding, for example, the science-philosophical status of a given concept or changes in the notion of mathematical proof? In order to find out, one would have to scrutinize the concrete use of an original source in a specific educational setting. Something similar goes for reason number 8 on *dépaysement*.

In fact, the idea of *dépaysement* is one which was originally suggested by Barbin (1997) and later translated and rephrased in Jahnke et al. (2000), as one of three general ideas for describing the special effects of using original sources:

- *Replacement* (in the original French wording, *vicariante*), which refers to the replacement of the usual with something different, for example, by allowing mathematics to be seen as more than just a corpus of knowledge and techniques.
- *Reorientation* (a translation of *dépaysement*), which challenges one's perception by making the familiar unfamiliar, eventually causing a reorientation of the reader's views and thus a deepening of the mathematical understanding – also sources remind students that mathematical constructs have come into being at one point in time (and space) and that this did not happen by itself.
- *Cultural understanding* (*culturel*), which allows us to place the development of mathematics in a scientific, technological, or societal context of a given time and place and in the history of ideas and society.

As we shall see in the given examples of the following sections, the idea of *dépaysement* is indeed a central one regarding the benefits of using original sources. As the reader may already have noticed, there is some variation in the interpretations of Jahnke et al. (2000) and Pengelley (2011). While Jahnke et al. talk about a *re*orientation and making the familiar unfamiliar, Pengelley refers to a *dis*orientation and mentions cognitive dissonance and multiple points of views. One reason for this variation may be that the idea of *dépaysement* involves a *process*. The first element is of course that of putting the student on unfamiliar ground, which is done by exposing him or her to an original source. This can indeed involve making the familiar unfamiliar. An example of this might be that of the notion of limits in real analysis: A student, who is used to the modern-day common notion, relying on Weierstrass' ε-δ-approach, may find that this becomes very unfamiliar, when seeing the earlier ideas of infinitesimals as discussed by, for example, Leibniz in his version of calculus. According to Furinghetti, Jahnke, and van Maanen:

> There are many experiences which show that students are motivated to reflect about the limit approach to calculus when they study Leibniz' way of dealing with infinitely small quantities. Also the teacher may gain insight by concentrating on the unfamiliar. It is often difficult enough to cope with unexpected solutions by students; however, studying sources enables to the teacher and students to keep an open mind. (Furinghetti et al. 2006, p. 1286)

Indeed, such a study may cause a cognitive dissonance, because the student is suddenly exposed to two different mathematical discourses. Sfard (2008) refers to such a situation as a *commognitive conflict*[24] – a situation where different discursants are acting according to different *meta-discursive rules* (not to be confused with the previously introduced meta-issues of mathematics) of mathematical discourse, which are historically given rules about proper communicative actions shaping the mathematical discourse, rules governing when to do what and how to do

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[24] The word commognitive relates to *commognition*, which is a contraction of *communication* and *cognition*, and which means to stress the fact that communication and cognition are different intrapersonal and interpersonal manifestations of the same phenomenon (Sfard 2008).

it, and which are implicitly present in discursive actions of the mathematists.[25] Surely, such experience of cognitive dissonance, or an encounter with a commognitive conflict, may cause disorientation on the students' behalf, which should be seen as a good thing, since disorientation often is a precursor for reorientation. And of course, such reorientation may involve the development of multiple points of view on a mathematical topic, as, for example, that of the notion of limit in real analysis.

The example of the notion of limit above may of course hold in it the dimension of replacement also, since the student's idea is replaced by a different one.[26] As for cultural understanding, however, more would be needed in order to develop a student's perception of it in relation to the notion of limits.[27] For example, one might focus on the relevance of extra-mathematical phenomena for the development of limits, applicational uses, or the scientific importance of the notion. Thus, while both replacement and *dépaysement* seem to hold in them a natural focus on mathematical in-issues, cultural understanding appears to focus more specifically on the meta-issues. However, in a setting of using original sources, a true understanding of the involved meta-issues may often not be reached if the involved mathematical in-issues are not understood to some degree. For instance, if one wishes to make sense of why it was Weierstrass' ε-δ-approach that eventually became the standardized one in real analysis and not the rival one of infinitesimals (except in non-standard analysis), one will need to understand the two different notions. Another way of phrasing this is to say that the meta-issue context is rooted or *anchored* in the in-issue context (Jankvist 2011). Of course, the converse may also be true that the in-issues of an original source can be rooted in the meta-issue context surrounding it.

The various reasons discussed above do, of course, *not* make up a complete list of every possible reason one might think of in relation to the use of original sources in the teaching and learning of mathematics. Still, it illustrates that the reasons for doing so are not only multiple but also multifaceted. And the analysis of the discussed reasons illustrates that they may be viewed as focusing mainly on aspects of meta-issues or of in-issues. Regarding the in-issues, we shall later see that these may also be discussed in terms of the use of original sources contributing to the development of students' mathematical competencies. Furthermore, by relating to the three general ideas of Barbin (replacement, *dépaysement*, cultural

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[25] A *mathematist* is a participant in mathematical discourse including students, teachers, and mathematicians (Sfard 2008).

[26] Furinghetti et al. (2006) give the example of Newton's letter to Leibniz of 1676 in which he describes how as a young man of 22 years; he arrives at the general binomial formula (a cornerstone in his fluxional calculus) as an example of possible replacement, since it is a unique document for a process of mathematical innovation progressing by bold generalizations and analogies.

[27] In relation to cultural understanding, Furinghetti et al. (2006, p. 1286) mention Heron's textbook (first century A.D.) on land surveying called *The Dioptra*. Reading parts of this, they say, "connects the topic of similarity to the context of ancient surveying techniques and shows the astonishingly high achievements of ancient engineers in this and other areas. Such sources may as well provoke students to engage in practical activities (simulations, measurements, theatre), which otherwise would not come to their mind or to the mind of their teacher."

understanding), we are able to conduct a more detailed analysis of the various reasons – or purposes – of using original sources, by placing a given use within one of the three general ideas, and then try to sort out how much focus must be (or was) put on in-issues and meta-issues, respectively.

But before we get to some illustrative examples of actual uses of original sources with students, we should look at some of the approaches to using original sources.

27.5 Various Approaches to Using Primary Original Sources

In this section, we shall have a look at some of the approaches usually discussed in the literature for using original sources in the teaching and learning of mathematics. Surely a different selection could have been made, but the one below offers both longtime well-known and more recently developed approaches, the latter of which also relates to later examples. It is important to mention that there may be overlaps between the approaches given and that some of them may resemble "philosophies" about the inclusion of original sources (or history), while others may be seen more as methodologies, methods, or models, e.g., for addressing practical issues associated with using original sources or for reaching specific goals by using such sources. Nevertheless, since all usually are referred to as *approaches* in the literature, the same is done here, although the reader shall be notified which approaches are more heavy on philosophy and which on methodology, based on the given descriptions.

Before we get to the descriptions, a certain notion from historiography must be introduced, namely, that of *Whig* history. This notion is due to the British historian Herbert Butterfield who defined it as a way of "measuring" the past in terms of the present (Butterfield 1931/1951). A well-known example hereof is that of the Bourbaki approach to the history of mathematics, in particular with Jean Dieudonné and André Weil. In a discussion related to why and how history of mathematics should be conducted, Weil, for instance, claimed that

> … it is impossible for us to analyze properly the contents of Book V and VII of Euclid's without the concept of group and even that of groups with operators, since the ratios of magnitudes are treated as a multiplicative group operating on the additive group of the magnitudes themselves. (Weil 1978, p. 232)

The problem partly consists in that one comes to follow a path from the present back to the past, where the only things which are considered are those which lead to something deemed significant today, whereas "from the perspective of the past, and that is the *historical* perspective, it is a zigzag path of a wanderer who does not know where exactly he is going" (Fried 2001, p. 396, italics in original). Thus, if we, in the context of introducing a historical dimension in mathematics education, wish to be honest to history, i.e., adopt a genuine historical perspective, we may be much better off resorting to primary original sources, since these are open to the reader's own interpretation – an interpretation which in its outset is not Whig. Also, the notion of Whig history may be used as a sort of measure of various approaches for using original sources; in the sense that while several in-issues might very well be brought forth in a Whig approach to history, the reaching of meta-issues often requires in its outset a non-Whig approach.

27.5.1 The Genetic Approach

One of the oldest approaches to including history through a use of original sources is the so-called genetic approach, which was strongly advocated by the German mathematician Felix Klein (Schubring 2011), for example, in his *Elementarmathematik vom höheren Standpunkte aus*,[28] where he argued for a genetic method of teaching wherever possible (Klein 1908). A more theoretically reflected conception of the genetic approach was formulated by another German mathematician, Otto Toeplitz. According to Burn (1999, p. 8), "the question which Toeplitz was addressing was the question of how to remain rigorous in one's mathematical exposition and teaching structure while at the same time unpacking a deductive presentation far enough to let a learner meet the ideas in a developmental sequence and not just a logical sequence." Worth noting is that Toeplitz distinguished between a *direct* genetic method and an *indirect* genetic method:

> [A]ll these requisites […] must at some time have been objects of a thrilling investigation, an agitating act, in fact at the time when they were created. If one were to go back to the roots of the concepts the dust of times […] would fall from them and they would again appear to us as living creatures. And from then on there would have been offered a double road into practice: Either one could directly present the students with the discovery in all of its drama and in this way let the problems, the questions, and the facts rise in front of their eyes – and this I shall call the *direct genetic method* – or one could by oneself learn such an historical analysis, what the actual meaning and the real core in every concept is, and from there be able to draw conclusions for the teaching of this concept which as such is no longer related to history – the *indirect genetic method*. (Toeplitz 1927, pp. 92–93, my translation from German)

In relation to the use of original sources, it is of course the direct genetic approach which is of interest. Tzanakis (2000) describes the genetic method as one in which there is no uniquely specified way of presentation in the sense of an algorithm; rather, it is a general attitude towards the presentation of a scientific subject. In that way, the motivation behind introducing new concepts, theories, or key ideas of proofs is based on their genesis and evolution. Toeplitz points out that nothing is further from his thoughts than giving a lecture on history. Instead, he wants to "…pick from history only the basics of those things that have stood the test of time and make use of them" (Toeplitz 1927, p. 95). Thus, the genetic method is not one concerned with getting messages related to meta-issues across to the students, but instead it is using history as a tool – and therefore also original sources – to teach and have the students learn mathematical in-issues.

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[28] Usually translated to: *Elementary Mathematics from an Advanced Standpoint.*

However, as pointed out by Glaubitz (2011), Toeplitz' approach implicitly assumes that there is a "great ascending line" in history to follow, which there often is not, in which case "important stages" will have to be identified instead. Although it may be possible to identify such important stages – or key points or crucial steps, which acted as a catalyst for further progress in the historical development[29] – as in any situation where an interpretation is made of what is historically important and what is not, Whiggishness may be lurking, since such interpretation is often made from a contemporary point of view. Of course, when using primary original sources in the teaching and learning, this ought to be less likely to happen.

27.5.2 The Hermeneutic Approach

Somewhat in contrast to the genetic approach is the so-called hermeneutic approach,[30] as proposed by Hans Niels Jahnke (also in Jahnke et al. 2000) – an approach which concerns itself with meta-issues as well as in-issues of mathematics. Glaubitz describes the difference between the hermeneutic and the genetic approach as follows:

> … the big difference to the genetic approach is, that the students are not expected to trace a history of thoughts that leads them from past roots to the standards of today. Essentially that is, because the students should be very familiar with a topic before they even touch a historical text that deals with it. In the hermeneutic approach, students are asked to examine a source in close detail and explore its various contexts of historical, religious, scientific etc. nature. In hermeneutics this is called: to move within hermeneutic circles – and these are circles of ever new understanding. (Glaubitz 2011, p. 357)

Jahnke relates the idea about hermeneutic circles to original sources in the following manner:

> The process of interpreting an original mathematical source may be described by a twofold circle […] where in the primary circle a scientist (or a group of scientists) is acting and in a secondary circle the modern reader tries to understand what is going on. (Jahnke 2000, p. 298)

Following Schubring (2005), the key idea is to approach the intended meaning of the original source, this being in the primary circle, and for the modern-day reader to perform hermeneutical reconstructions of how concepts (and other mathematical in-issues) developed. It is worth noticing that being this alert of the shifting within circles makes the reader's interpretation much less prone to becoming Whig.

Due to the fact that within the hermeneutic approach, students need a prerequisite knowledge of the topic, Glaubitz explains that the approach is often applied

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[29] See in particular Sect. 7.3 of Fauvel and van Maanen (2000) and Tzanakis and Thomaidis (2000).

[30] The hermeneutic approach is sometimes also referred to as the historico-hermeneutic approach.

only to subject matters with which the students are already familiar. He further describes the hermeneutic approach as essentially consisting of three steps:

> Usually the structure is as follows: First, the students have a quite conventional introduction to the topic. No history is involved until the second step, in which the students read a historical source. In this source, the same topic is covered, but in a way, that is historically distant, different in its representation, used in strange contexts and so forth. This is the step where the students' epistemic curiosity is – hopefully – aroused. In the third and final step students are required to explore the source in even greater detail, perform a horizon merger and reflect upon questions that occur to them. (Glaubitz 2011, p. 358)

The term "horizon merger" refers to a student's development of deeper awareness by wondering and reflecting about what she/he never thought about before (Gadamer 1990). Thus, in relation to the previously discussed reasons for including primary original sources, we notice the presence of the arguments of replacement and *dépaysement* in the hermeneutic approach.

27.5.3 Multiple-Perspective Approach

Recently, Kjeldsen has been arguing strongly for what she refers to as a *multiple-perspective approach* to history, including also the use of primary original sources in the teaching and learning of mathematics (e.g., Kjeldsen 2009a, b and 2011a, b, c; Kjeldsen and Blomhøj 2012; Jankvist and Kjeldsen 2011). Contrary to the hermeneutic approach, students do not necessarily need to possess prerequisite knowledge of the modern interpretation of the topic they are about to study through original sources. One similarity between the two, though, is that they both approach original sources from a somewhat micro-historical point of view – or *views* – since Kjeldsen by multiple perspectives is referring to the analysis and consideration of the practice of mathematical activities at a given time and place from several points of observation or contexts:

> The perspectives can be of different kinds and the mathematics can be considered from different angles, such as various sub-disciplines of mathematics, techniques of proofs, applications, "nature of mathematics" positions, other scientific disciplines, sociological institutions, personal networks, genders, religious beliefs and so on. This approach to history raises the question of which perspectives to choose, since, of course, not every perspective that one can think of is necessarily interesting (or accessible) regarding a particular historical analysis. A way to handle this difficulty when using history in mathematics education is to adopt a problem-oriented approach, that is, to have clearly formulated historical research questions and then to focus on perspectives and to choose historical episodes that explicitly address and relate to the issues one wants students to reflect upon. (Kjeldsen and Blomhøj 2012, p. 332)

Examples of such problem-oriented "research questions" to focus on while reading and studying primary original sources could be

> … why mathematicians asked the questions they did; why they treated the problems they dealt with in the way they did; what kinds of proofs or arguments they gave, and how these were perceived and received within the mathematical community(ies); why they introduced

> certain mathematical objects, definitions, areas of research etc.; and how all of the above influenced further developments in mathematics as well as changes in perceptions of mathematics. (Jankvist and Kjeldsen 2011, p. 836)

One historical framework which is particularly interesting in relation to the multiple-perspective approach is that of *epistemic objects and epistemic techniques*, originally developed by Rheinberger (1997) for the study of experimental sciences but adapted by Epple (2004) to the historiography of mathematics. Epistemic objects refer to the mathematical object(s) under investigation by the mathematician(s) in a given time and space. Epistemic techniques refer to the methods and tools that were used to study the object(s), either well-established techniques or techniques which have to be developed in the process of studying the object(s). Together, the epistemic objects and techniques constitute what Epple calls the *epistemic configuration*. This is where the (groups of) mathematicians (pure or applied), within a given space and time, perform their work – their "intellectual working place" or "mathematical workshop." It is important to notice the dynamical process inherent in the notions of epistemic objects and techniques, meaning that what in one historical setting functioned as objects might be turned into techniques later or in another setting (e.g., Epple 2004; Kjeldsen 2009b). Besides making up a non-Whig approach to the historiography of mathematics, the multiple-perspective approach is also extremely suitable for focusing on both mathematical in-issues and meta-issues when using primary original sources in mathematics education, e.g., in Epple's framework, by considering the epistemic objects and techniques themselves and then considering (cultural or societal) aspects surrounding the epistemic configuration, respectively. (The notion of objects and techniques shall be illustrated in the section on examples.)

27.5.4 Comparative Readings of Original Sources and Other (Kinds of) Texts

Whereas the three approaches discussed above are more general approaches – or "philosophies" – to the use and studying of original sources in mathematics education, the following ones are more specific in nature and more methodological. The first one concerns comparisons of different kinds of texts, which Jahnke et al. (2000) discuss in terms of the benefits of comparing original sources with secondary sources, for example, books on the history of mathematics. In contrast to merely relying on such secondary sources, the study of primary original sources helps to:

(a) Clarify and extend what is found in secondary material,
(b) Uncover what is not usually found there,
(c) Discern general trends in the history of a topic (secondary sources are usually all-topic chronological accounts, and some topics are very briefly treated or omitted altogether), and
(d) Put in perspective some of the interpretations, value judgments or even misrepresentations found in the literature. (Jahnke et al. 2000, p. 293)

As may be derived from the points above, a *comparative reading* of primary original sources with secondary literature may be quite rewarding for students (and teachers as well).

Comparison of an original source with a (modern) textbook's presentation of the topic in the original source may also be a sensible task to undertake. In relation to the previously mentioned *dépaysement*, Barnett, et al. (2011) state that it may

> Engender cognitive dissonance (dépaysement) when comparing a historical source with a modern textbook approach, which to resolve requires an understanding of both the underlying concepts and use of present-day notation. (Barnett et al. 2011, p. 188)

A more compelling reason for resorting to primary original sources over textbooks – and some secondary literature, depending on its nature – is the one pointed to by Fried (2001), namely, that textbooks by definition are *closed to interpretation*, since they merely set out to present already accepted knowledge. Primary original sources, on the other hand, which convey their own order of inquiry, are open to the reader's own reflections in a very different sense, through the author's original language of discovery and invention.

A comparative reading of primary sources with other primary sources may enhance the effect of these in relation to the originally intended purposes of resorting to primary original sources. If, for example, the intention was one of the meta-issues regarding the development of mathematics (and science), a comparison of two original sources addressing the same problem, and possibly developing the same or similar theoretical constructs, could lead to a discussion of *multiple discoveries* (e.g., Merton 1973). One example of that is the well-known one of Newton's and Liebniz' simultaneous, but very different, developments of the infinitesimal calculus. Another example of comparing different original sources might be when comparing various translations of the same source to observe how cultural aspects have influenced such translations. An example of this may be found in Siu (2011), who discusses the translation of the first European text in mathematics (Euclid's *Elements*) into Chinese, by comparing the different ways of mathematical thinking, the different style of presentation, and the different views of mathematics in the East and in the West.

27.5.5 Guided Readings of Primary Historical Sources

The second of the methodological approaches is the so-called *guided readings* of original sources developed by David Pengelley, Janet Barnett, Jerry Lodder, and colleagues (see, e.g., Barnett et al. 2011; Knoebel et al. 2007; Laubenbacher and Pengelley 1999).[31] This method offers a sensible way of dealing with the occasional inaccessibility of primary original sources. The idea is to supply or "interrupt" the students' reading of an original source by explanatory comments and illustrative tasks along the way. The group surrounding Pengelley, Barnett, Lodder, and colleagues

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[31] See also http://www.cs.nmsu.edu/historical-projects/papers.html (Retrieved on February 1, 2012).

has developed numerous teaching modules (or projects), ready for implementation in class (undergraduate level or high school). And one of the beautiful things about their work is that they have an "open-source" policy, providing teachers and other researchers with free access to the LaTeX code of their modules, and invite them to adapt it for their own use and to share their experiences.[32] (Examples of sources which have been subject to such guided readings will be given in the following section.)

27.5.6 Essay Assignments Related to Readings of Original Sources

While the approach of guided readings originally was developed to make the mathematical in-issues of the original source more accessible and understandable to the students, the third methodological approach to be discussed here, that of *essay assignments*, was developed from the point of view of bringing out meta-issues. In a study I carried out in 2007 (and which is reported in Jankvist 2009b, 2010, 2011), focus was on creating a setting where upper secondary school students could come to discuss and reflect upon historical, philosophical, and/or applicational meta-issues of the mathematics they had studied through the use of excerpts from original sources. This was realized by having groups of students write essays (a couple of pages long) answering a series of questions on meta-issues as part of their mathematics class. For example, in a historical teaching module on the development of public-key cryptography (Diffie, Helman, and Merkle; Rivest, Shamir, and Adleman) and the underlying number of theoretical constructs (e.g., stemming to Sun Zi; Fermat, and Euler), students were asked to discuss these researchers' motivations for engaging into their studies of topics from the point of view of *inner driving forces* in the discipline of mathematics and *outer driving forces*, i.e., influence on the development of mathematics from the outside due to societal needs (Jankvist 2011). Thus, this study also adopted the multiple-perspective approach to history of mathematics (for further discussion in relation to this particular historical case, see Jankvist and Kjeldsen 2011). Also, within the setting of the multiple-perspective approach, I have used a design combining the idea of guided readings of primary original sources and the use of essay assignments (Jankvist 2013), which will be illustrated in the following section.

27.6 Illustrative Examples of Didactic Design and Findings from Using Primary Original Sources

To illustrate actual uses of original sources in the teaching and learning of mathematics, a small selection of more recent examples from the literature will be described and discussed. These examples have been chosen to illustrate some of the

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[32] Links are http://www.math.nmsu.edu/hist_projects/ and http://www.cs.nmsu.edu/historical-projects/ (Retrieved on February 1, 2012).

different uses in terms of purposes and approaches (cf. previous sections), whereas not much emphasis has been put on choosing examples from many different national settings, since interested readers may already find a cohort of such examples displayed in the ICMI Study (Fauvel and van Maanen 2000).[33] Also, since the ICMI Study offers a long list of examples regarding uses of original sources to support understanding of various important mathematical concepts from the perspective of students as well as teachers, the following examples were not chosen with this in mind. Instead, focus has been on the illustration of didactic designs and didactic findings related to the use of original sources in the teaching and learning of mathematics. However, some effort has been made to illustrate the use of original sources at different educational levels: primary, secondary, and tertiary level. Furthermore, an important element in some of the chosen examples is the adherence to a theoretical framework from mathematics education research – an aspect to be discussed in the final section of this chapter.

27.6.1 An Interdisciplinary Reading of Bartolus of Saxoferrato in Dutch Grammar School

On several occasions, van Maanen has described his use of the history of mathematics through primary original sources in upper secondary classrooms (examples are van Maanen 1991, 1997). In a paper appearing in the collection edited by Swetz et al. (1995), van Maanen continues his descriptions based on personal experiences with three historical cases: seventeenth-century instruments for drawing conic sections, improper integrals, and one on the division of alluvial deposits in medieval times. The latter, which shall be discussed in more detail, is different from the other two in that it describes a project in three first-year classes of the Dutch grammar school, pupils about age 11, and because it was an interdisciplinary project with Latin.

In a medieval setting of a case of three landowners, who all had land on the bank of a river, fighting over an alluvial deposit bordering their land, the students were to investigate the problem by means of a method proposed by the Italian professor Bartolus of Saxoferrato in 1355 (the example with the landowners was the one used by Bartolus himself). The ideas of the project, as described by van Maanen, were to demonstrate the importance of mathematics in society, which relates to Barbin's idea of cultural understanding (meta-issues); to let pupils "invent" a number of constructions by ruler and compass, thus emphasizing the importance of understanding mathematical in-issues; to have them apply these "inventions" in order to solve the legal problem of the medieval example, which illustrates the applicational dimension of mathematics as a discipline; and to have them read excerpts from Bartolus' treatise in the original Latin language, illustrating "that it is impossible to interpret the sources of Western culture without knowledge of classical languages" (van Maanen 1995, p. 79), clearly, yet another meta-issue and as such, one which would

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[33] Of course a factor in choosing these exact examples is my own familiarity with them, which enables me to perform a deeper analysis of the underlying motives for resorting to original sources.

be very difficult to illustrate without resorting to original sources. Van Maanen's evaluation of the implementations of the project is

> Making contact with Bartolus was only possible via deciphering and translating, but that was simply an extra attraction to most of the pupils. They learned to work with point-sets in plane geometry, and simultaneously their knowledge of general history increased. Last but not least, they were greatly stimulated to learn Latin. (van Maanen 1995, p. 80)

27.6.2 The Early History of Error-Correcting Codes: Working with Excerpts in Upper Secondary School

The next example is a teaching module for Danish upper secondary school (described in Jankvist 2009b; 2010). The module deals with the early history of error-correcting codes, and as part of it, the students were to read excerpts from original sources by Shannon, Hamming, and Golay. The historical background is that based on Shannon's display of Hamming's so-called (7,4) error-correcting code[34] in 1948, Golay was able to make the generalization of this into the entire family of Hamming codes in 1949 and discover a few additional codes himself. Due to the wish of the Bell Laboratories, wanting to patent Hamming's codes, his own publication was delayed until 1950 (which later caused a quarrel regarding who was in fact the originator of the codes). Having read excerpts from these sources (in translation), the students were to do an essay assignment, identifying and discussing epistemic objects and epistemic techniques in Hamming's development of the (7,4) code, the object being the code itself and the techniques the notion of metric and elements of linear algebra. One of the objectives of this essay assignment was for the students to make a distinction between the already available techniques, i.e., the well-established mathematics that Hamming was using and the techniques that he himself had to create in the process. One group of students who did rather well in making this distinction answered:

> Hamming uses generalized concept of distance; elements of linear algebra; geometrical models; and unity n-dimensional squares.
> A metric which is called a distance $D(x, y)$ is the definition of Hamming distance.
> Since x and y must be different ($x \neq y$), we can find how similar the two codes are, because we talk about a more generalized concept of distance.
> Linear algebra is concerned with the study of addition and proportionality, and it is the concept of linearity that binds the concepts of addition and proportionality together.
> We use geometrical figures to understand the n-dimensions, since these exceed what can be understood physically, i.e. 1st, 2nd, and 3rd dimension.
> n-dimensional cube is the same as the metric space. (Group 5, translated from Danish. Quoted from Jankvist and Kjeldsen 2011, p. 853)

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[34] In this binary code, all code words consist of seven bits, four of these being information bits, hence the name (7,4)-code.

Of course, not all groups were able to distinguish in an equally clear manner the already available techniques from those constructed by Hamming in the process and therefore might list Hamming's own constructs as being already available (for an example, see Jankvist and Kjeldsen 2011). A long discussion of the mathematical in-issues mentioned in the quote above shall not be given, but despite that, it should still be clear that without an understanding of these in-issues on the students' behalf, it is not possible for them to enter into the meta-issue micro-historical discussion of Hamming's error-correcting codes coming into being. This multiple-perspective approach to mathematics through its use of essay assignments thus illustrates mathematical understanding as a prerequisite condition for deeper cultural understanding. Or to phrase it differently, an understanding of the meta-issues is *anchored* in an understanding of the in-issues (Jankvist 2011).

27.6.3 Project Work on Bernoulli's Solution of the Catenary at University Graduate Level

In the setting of students' problem-oriented project work at Roskilde University (Denmark), Kjeldsen (2011a, b) has discussed the learning outcome of five graduate students enrolled in the mathematics program while doing a project based on readings of three original sources from the 1690s: the solutions to the brachistochrone problem[35] by Jakob Bernoulli and Johann Bernoulli, respectively, and Johann Bernoulli's solution to the catenary problem[36] (see also Jankvist and Kjeldsen 2011; Kjeldsen and Blomhøj 2009, 2012). More precisely, Kjeldsen has addressed the learning outcome from two different mathematics educational perspectives: the development of students' mathematical competencies (Niss and Højgaard 2011) and students' learning of meta-discursive rules in mathematics (Sfard 2008).

The framework of students' *mathematical competencies,* as described by Niss and Højgaard (2011), lists eight mathematical competencies: mathematical thinking competency, problem-solving competency, modeling competency, reasoning competency, representation competency, symbols and formalisms competency, communication competency, and aids and tools competency. A mathematical competency is defined as "having knowledge of, understanding, doing, using and having an opinion about mathematics and mathematical activity in a variety of contexts where mathematics plays or can play a role," or in other words a kind of "well-informed readiness to act appropriately in situations involving a certain type of mathematical

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[35] The *brachistochrone problem* (from Greek *brachistos* meaning shortest and *chronos* meaning time) is to find the curve by which a particle under influence of gravity will travel the fastest from a given point A to a given point B. The curve is the so-called cycloid, and the solution to the problem was found not only by the Bernoullis but also by both Newton and Leibniz around the same time (another example of multiple discoveries).

[36] The *catenary problem* consists in describing the curve formed by a flexible chain hanging freely between two points.

challenge" (Niss and Højgaard 2011, p. 49). In relation to the students' reading of Johann Bernoulli's original text on the catenary problem, the students' development of four of these eight competencies took place in the following way:

> The students' *problem solving* skills were trained extensively in their work with Bernoulli's text on the catenary. As emphasized above, the students had to fill in all the 'gaps' in Bernoulli's presentation in the course of which the students derived several intermediate results themselves. [...] Parts of the students' *mathematical modeling* competency were developed through their struggle to understand Bernoulli's mathematization of the physical description of the catenary, and to justify his five assumptions from statics. [...] Their *mathematical reasoning* competency was developed, in particular through their struggle to clarify the apparent lack of rigor in Bernoulli's way of arguing compared with modern standards. Bernoulli's way of argumentation is not in accordance with what is considered 'proper' or rigorous mathematical reasoning today. [...] The students' ability to distinguish between and utilize different *representations* of e.g. mathematical objects was especially challenged in [...] their study of Bernoulli's construction of the solution to the differential equation of the catenary. Here they experienced a representation of a solution that is quite different from the analytical representation they usually see in modern textbooks. (Jankvist and Kjeldsen 2011, pp. 843–844)

As evident from the quote, the development of these competencies is tightly connected to the studying of the original source, some even a direct consequence thereof. (For a discussion of the students' development of the four remaining competencies due to this project work, see Kjeldsen 2011a.) From the point of view of using history as a tool for teaching and learning mathematical in-issues, students' competency development provide a different – and possibly more natural – means for evaluating the use of original sources than just assessing students' conceptual understanding.[37]

In relation to the previous discussion of *dépaysement*, the definitions of Sfard's (2008) notions of *meta-discursive rules* of mathematical discourse and *commognitive conflict* have already been given (please refer to these if needed). In the context of the same students' reading of Bernoulli's solution of the catenary, Kjeldsen and Blomhøj explain that the learning of meta-discursive rules

> ... is difficult, and as pointed out by Sfard, because of the contingency of meta-level rules, it is not likely that learners by themselves will begin a meta-level change. Such a change is most likely to happen when (or if) the learner experiences another (new) discourse that is governed by meta-rules other than those the learner so far has been regulated by. An experience like that constitutes what Sfard (2008, p. 256) calls a commognitive conflict, which she defines as "a situation in which different discursants are acting according to different metarules." (Kjeldsen and Blomhøj 2012, p. 330)

Such commognitive conflicts may of course also arise when students compare discourses of different discussants, for example, when comparing different original sources as mentioned earlier. However, the occurrence of commognitive conflicts is to a large extent dependent on and conditioned by a non-Whig approach to history, because

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[37] Niss and Højgaard (2011) give three dimensions for assessing a person's mastery and development of a competency: degree of coverage, radius of action, and technical level.

> If one's reading and interpretation of historical sources are constrained by the way mathematics is perceived and conceptualised in the present, the historical text cannot play the role of an "interlocutor" that can be used to create commognitive conflicts [. . .] when students "communicate" with the text, since differences in the way of communicating in the past and in the present will have been "washed away" by the whig interpretation. (Kjeldsen and Blomhøj 2012, p. 331)

Thus, original sources, or alternatively secondary sources which are very close to the original, come to play an almost indispensible role in this setting of developing students' understanding of meta-discursive rules through a use of history of mathematics.

As an addendum, the role of the original source as an *interlocutor* is also discussed by Jahnke et al. (2000, p. 296), who say that "a source can be a trigger for establishing a dialogue with the ideas expressed" and it "then becomes an interlocutor to be interpreted, to be questioned, to be answered and to be argued with." Jahnke et al. state that the role of a source as an interlocutor in particular applies to issues such as the nature of mathematical objects and the essence of mathematical activity, that is to say matters related to the meta-issues of mathematics. But as seen from the example of Kjeldsen and Blomhøj (2012), original sources as interlocutors may play an equally important role in relation to mathematical in-issues. However, a word of caution should be provided, because until recently history of mathematics has primarily been carried out by professional mathematicians in the Whig tradition (cf. the quote by Weil above). Unfortunately, this also has consequences for translations of sources and consequently for their roles as interlocutors. Schubring (2008), for example, points out that contrary to their claim of being accurate, some translations of well-known historical classics exist that have distorted the original sources.

27.6.4 Projects on Boolean Algebra and Electric Circuit Design at Undergraduate Level

The next example is situated in the context of teaching US undergraduate students with projects based on guided readings of original sources (cf. earlier). Janet Barnett has developed several such projects (see Barnett et al. 2011), and in the following we shall look at two of them.

In the first one, she deals with the origin of Boolean algebra by guiding students through carefully chosen parts of Boole's 1854 treatise on the "*Laws of Thought"* (Barnett 2011a). Boole introduces a new algebra by explaining the use of "signs" to represent "classes" and by defining a system of symbols (+,–,×, 0, 1) to represent operations on these signs and finally deducing the basic laws that the operations must follow. While so doing, Boole continuously compares his new algebra to standard arithmetical algebra,[38] one of the main differences being that in Boole's algebra

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[38] One might talk about a built-in replacement and *dépaysement* in Barbin's sense in Boole's own presentation of his algebra.

we have that $xx=x$ (or $x^2=x$), because if, for example, x stands for "good," then saying "good, good men" is the same as saying "good men." Knowing that this can only be so if x is either 0 or 1, Boole draws the consequence by conceiving an algebra where symbols x, y, z, etc. admit indifferently of the values 0 and 1, and of these values alone, and carries on to deduce a series of laws. Barnett's (2012, p. 344) ultimate goal of this project is to have the students "develop an understanding of the modern paradigm of elementary set theory as a specific example of a Boolean algebra," and for that reason she has students study original sources of both Venn and Peirce next, as part of the project.

In the other project of Barnett's which is mentioned here, she has students read part of Shannon's famous 1938 article on design of electric circuits by means of simplification through Boolean algebra (Barnett 2011b). Using a set of postulates from Boolean algebra ($0 \cdot 0=0$; $1+1=1$; $1+0=0+1=1$; $0 \cdot 1=1 \cdot 0=0$; $0+0=0$; and $1 \cdot 1=1$) and interpreting these in terms of circuits ($0 \cdot 0=0$ meaning that a closed circuit in parallel with a closed circuit is a closed circuit and $1+1=1$ meaning that an open circuit in series with an open circuit is an open circuit), Shannon is able to deduce a number of theorems which could be used to simplify electric circuits.

From studying these two projects by Barnett, it is clear that focus is on the in-issues as she guides the reader through the original texts and eventually leads him or her up to a, in the first project, modern account of the algebra of logic, set theory, and Boolean algebra of today and in the second project to relating Shannon's original representation of connections in series and in parallel to that of today as well as introducing truth tables in the guiding tasks. Regarding the first project, Barnett says that it

> … provides an opportunity for students to witness how the process of developing and refining a mathematical system plays out, the ways in which mathematicians make and explain their choices along the way, and how standards of rigor in these regards have changed over time. (Barnett 2012, p. 344)

However, the in-issue focus must also be seen as a natural consequence of the educational setting for which the projects are designed – undergraduate students following courses relying on such projects will eventually have to follow several traditionally taught courses relying on modern-day textbooks, for which they need to know modern-style notation and standards for proof. Nevertheless, the approach of guided reading still leaves the excerpts from the original sources completely untouched, potentially enabling students to make their own interpretations along the way.

27.6.5 HAPh Modules and the Development of Upper Secondary Students' Overview and Judgment

The final example concerns students' reading of some of the same original sources as those used by Barnett but in the setting of Danish upper secondary school. The motivation for this use of original sources was twofold: to design teaching modules focusing on meta-issues of history, applications, and philosophy of mathematics in unison (Jankvist 2013) and to measure the effect of such modules on the students' development of what Niss and Højgaard (2011) term "overview and judgment" (Jankvist 2012a). The notion of overview and judgment stands in contrast to the previously mentioned one of mathematical competency, in that these do not concern "readiness to act" but instead are "'active insights' into the nature and role of mathematics in the world" which "enable the person mastering them to have a set of views allowing him or her *overview and judgement of the relations between mathematics and in conditions and chances in nature, society and culture*" (Niss and Højgaard 2011, p. 73, italics in original). Niss and Højgaard deal with three types of overview and judgment, which have already been exemplified in the quotes given when introducing the notion of in-issues and meta-issues earlier:

- The historical evolution of mathematics, both internally and from a social point of view
- The actual application of mathematics within other subjects and practice areas
- The nature of mathematics as a subject

The design encompassing all three of these dimensions – referred to as *H*istory, *A*pplication, and *Ph*ilosophy (*HAPh)* – was based on an observation that the inclusion of these dimensions share an overlap in the so-called whys and hows, i.e., that similar reasons are provided for their inclusion and that similar approaches can be used (see Jankvist 2013). Further, it was argued that the use of original sources, one for each dimension, through a guided reading and a use of essay assignments was a suitable way of evoking the desired meta-issues.

In one such HAPh module, Boole's original text on the *Laws of Thought* made up the historical dimension and Shannon's 1938 article on electric circuit design the applicational dimension (cf. the previous illustrative example). The original source for the philosophical dimension was a paper by Hamming from 1980 in which he discusses *The unreasonable effectiveness of mathematics*[39] from the viewpoint of engineering (and computer science), asking why it may be that so comparatively simple mathematics suffices to predict so much, this question making up the "unreasonable" aspect. After discussing what mathematics is, Hamming provides some tentative explanations of why mathematics is in fact so effective (see Jankvist 2013). Based on their readings of these three original sources, students were to do essay assignments discussing if the idea of Boolean algebra and its later use in describing electric circuits may be seen as an example of the unreasonable effectiveness of mathematics and if so then why (for students answers and reflections, see Jankvist 2012b, 2013). In another HAPh module, the same class of students had previously worked with the beginning of graph theory (Euler), its later use in solving the shortest path problem (Dijkstra), and the role of mathematical problems (Hilbert).[40]

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[39] This paper was a comment to a paper by the physicist Wigner from 1960, who addressed *The unreasonable effectiveness of mathematics in the natural sciences*.

[40] For a description of this HAPh module, see Jankvist (2012a, 2013). See also Barnett (2009) for a project on graph theory.

Now, in order to actually try and measure any effect these HAPh modules may have had on the development of a class of upper secondary students' overview and judgment, one must of course have ways of both *accessing* and *assessing* such. The means for accessing the students' overview and judgment were a combination of questionnaires, asking questions related to each of the three types of overview and judgment (see Jankvist 2012a) and follow-up interviews before, during, and after the implementation of the HAPh modules.[41] As for assessment, it is argued in Jankvist (2012a) that it makes sense to address the development of overview and judgment as a combination of students' actual *knowledge* and their *reflected images of mathematics as a* (*scientific*) *discipline*, where the latter may be measured in terms of:

- The growth in *consistency* between students' related beliefs/views
- The extent to which a student seeks to *justify* his or her beliefs and views
- The amount of provided *exemplifications* in support of the beliefs and views a student holds, i.e., the beliefs appear to be held more evidentially

The mentioning of beliefs here of course refers to the vast amount of literature on students' beliefs (e.g., Leder et al. 2002). While *beliefs* are usually taken to be something rather persistent, meaning that they are not likely to develop and change over a short-time period,[42] *views,* on the other hand, may be taken to be something less persistent but with the potential to develop into beliefs at a later point in time (Jankvist 2009b, forthcoming). Thus, development in, and changes of, students' beliefs *and* views, in unison the reflected images, provides an insight into their overview and judgment. However, it is important to stress again that overview and judgment does not equal beliefs and views, since it also consists of the actual *knowledge* which the students possess in relation to both mathematical in-issues and meta-issues.

One question or topic which has proven itself particularly helpful in uncovering students' overview and judgment is that of mathematics being discovered or invented (e.g., Hersh 1997). To illustrate this, an excerpt from an interview with the upper secondary student Larry from when he had been through both HAPh modules is offered;

Interviewer	And you say about Boolean algebra that you believe it to be invented? […]
Larry	Yes, we define [it] ourselves. It's… We take a way of thinking and turn it into mathematics; this means this and that means that… Well, it might be that the way of thinking was already there, but we invent a way of writing it within mathematics. I'm not sure I can phrase it any better.
Interviewer	Okay. In question 26 you say that Boolean algebra, classes, etc. are human constructions, which of course is connected to what you just said. But do you believe mathematics in general to be something we invent, or are there also things in mathematics which we discover?

(continued)

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[41] In some instances it was also possible to perform methodological triangulation with other data sources such as students' hand-ins, student group essay assignments, and video recordings as exemplified in Jankvist (2009b).

[42] Evidential (or evidence-based) beliefs are, however, more likely to change than non-evidentially held beliefs (Green 1971).

(continued)

Larry	Well… There can be connections in mathematics which we discover. For example the equation with Euler's number in the power of π times i minus or plus 1 equals 0 [$e^{i\pi}+1=0$]. These are some interrelations which we have not made ourselves. It is a lot of independent things which we have found and which then fits together and reveals a beautiful connection. […] I think it is a good example of something which we just discover. As far as I know these [π, e, and i] were not that associated. But that they fit together in this way, it kind of shows… that there must be a… that no matter what, we did something right.
Interviewer	Yes?
Larry	So regarding invention or discovery in mathematics, I think… I think that some things are invented and some discovered. I will risk claiming that.
Interviewer	Alright. Can you give some examples?
Larry	Well… for example our way… in graph theory, to translate bridges into numbers and the way of writing it all up [the Königsberg bridge problem]. That is something we've made. While things as… what is a good example? Things as π is something we discovered. […]
Interviewer	Okay. Is it possible to say if one precedes the other? Does discovery precede invention or does invention precede discovery?
Larry	In most cases it must… well, not necessarily… With π, for instance, I guess that discovery was before invention, because… If we say that we invented, that we set a circle to 360°. But when we calculate π […] then we don't use the 360°, as far as I recall. […] It is different within different areas of mathematics, but with π I think we discovered that there was a connection first, and then we built on that. But it's quite related; when we choose something we quickly arrive at some further discoveries.

(Interview with Larry, November 16th, 2011, translated from Danish. Quoted from Jankvist 2012a, pp. 859–860)

The excerpt illustrates well how Larry is able to both justify and exemplify his beliefs/views regarding invention and discovery. In terms of *development* of overview and judgment, Larry had started off a year and a half earlier, before the HAPh modules, to believe mathematics to be mainly an invention. In between the modules, he shifted to believing in mainly discovery. But above we see him adopting a more reflected stance, arguing that mathematics can be both.[43] To illustrate discovery, he first mentions Euler's identity ($e^{i\pi}+1=0$) as something that he finds unlikely to have been invented (Euler's identity was not part of the HAPh modules). Later he carries on to elaborate on the number π in relation to discovery, and we get an example of the interplay of beliefs/views and knowledge, when he refers to his actual knowledge of our convention of 360° in a circle being unrelated to the appearance of the number π. As examples of mathematics which is invented, he refers to the cases of the HAPh modules: first, Boole's introduction of his new algebra and later Euler's approach to dealing with the Königsberg bridge problem. Such exemplification helps Larry to hold his beliefs and views more evidentially,

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[43] Although the dimension of consistency is not very present in the displayed interview excerpt above, a growth in consistency was present in general in the case of Larry (Jankvist 2012a).

which also assists him in justifying them as well as the development and changes in them.[44] Thus, in this respect the primary original sources play the role of *evidence* which, together with the knowledge students have acquired from studying them, comes to form the basis for developing their overview and judgment (For further discussion, see Jankvist 2012a).

27.7 Discussing the Past, Present, and Future of Using Primary Original Sources

Having now looked at the background, the various reasons and approaches for using primary original sources, and the selected illustrative examples of didactic findings, it is time to recapitulate and look at possible directions which the use of original sources may take in the future, i.e., other reasons than those already discussed. A handful of such different perspectives on the use of original sources shall be pointed to.

27.7.1 Expanding the Emphasis

As indicated, the main emphasis of the use of original sources has, until recently, been on the teaching and learning of mathematical in-issues, both in terms of students' understanding or sensemaking of mathematical concepts and notions as well as in terms of motivating these; it is clear that the experience of seeing how a certain mathematical construct was motivated historically can provide students with a deeper understanding of why this construct came to look the exact way it did.[45] What should be added is that original sources may offer *a truer mode of presentation* when compared to that of textbooks, which usually go as follows: definition(s), theorem(s), proof(s), and application(s). In reality, the historical development of a mathematical topic is close to being the reverse – as mentioned when discussing Pengelley's (2011) reason 9 earlier. With original sources' often built-in relation between theory and practice, definitions of concepts, theorems, etc. are motivated. They do not appear out of nowhere. This means that the study of original sources may have as an outcome that students become more willing to accept abstract mathematical constructs, since these come to appear as natural consequences of the mathematical investigations presented in the source.

With the ICMI Study of 2000, it became clear that *more empirical research was needed* on introducing a historical dimension into the teaching and learning of

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[44] In the case of non-evidentially held beliefs, justification might very well take place without exemplification (see Jankvist 2009b, 2012a).

[45] Take, for example, the concepts of function, limit, continuity, and not least uniform convergence (see, e.g., Katz 1998 or the appendix on uniform convergence in Lakatos 1976).

mathematics, including the use of original sources to do so.[46] One recent example is the study by Glaubitz (2011), in which he compared different approaches to the teaching of quadratic equations and the quadratic formula and found that pupils who had been taught with original sources through the hermeneutic approach scored higher in standard tests than a control group who had been taught with a conventional approach. Also, as illustrated with the previously provided examples, some of the empirical work which eventually followed has contributed in broadening the scope of using original sources. With the studies of Kjeldsen, for instance, focus is not only on students' understanding of mathematical in-issues but also on their development of mathematical competencies as a result of studying and working with primary original sources (Kjeldsen 2011a; Jankvist and Kjeldsen 2011). Further, the examples illustrated how original sources (and excerpts of such) may play a role in teaching students something about the meta-issues of mathematics as a scientific discipline; how to do this in such a manner that the students' discussions of these meta-issues are anchored in their understanding of the related mathematical in-issues (Jankvist 2011); and how teaching modules involving readings of original sources related to history, application, and philosophy in unison may assist in developing students' overview and judgment (Jankvist 2012a).[47]

27.7.2 The Role of Theoretical Constructs from Mathematics Education Research

Another important aspect, which the chosen examples illustrate, is the relationship between empirical studies on resorting to original sources and *the use of theoretical frameworks and constructs from mathematics education research*. The discussion and "measuring" of original sources' effect on students' development of mathematical competencies and overview and judgment as defined by Niss and Højgaard (2011) are examples of this (including the discussion of students' beliefs in relation to overview and judgment). And another example is the use of Sfard's (2008) theory of commognition to illustrate the (almost indispensable) role of original sources as different discussants in students' learning of meta-discursive rules (Kjeldsen and Blomhøj 2012). But it is not only the case that the use of mathematics education research frameworks may inform the use of original sources and history of mathematics in general, in the teaching and learning of mathematics; it is also the case that the history of mathematics and the use of original sources may inform mathematics education frameworks. An example of this may be found in the study by Clark (2012), who, in a setting of teacher education, has used excerpts from an original

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[46] Since then a handful of PhD theses to some degree addressing empirical aspects of using original sources (or excerpts of such) have appeared: Clark (2006), Glaubitz (2010), Gulik-Gulikers (2005), Jankvist (2009b), and Ta'ani (2011).

[47] For a much more detailed account of the empirical studies available in the field of history in mathematics education, see Jankvist (2012c).

source by al-Khwariszmi, presenting his methods for solving quadratic equations. Based on her findings, Clark argues that history of mathematics (including the study of original sources) is part of the "something else" in the framework of mathematical knowledge for teaching (MKT) (Ball et al. 2008), since it informs teachers in their instructional practice. Taking into consideration the obvious benefits of discussing the use of history and original sources in teacher training within the framework of teachers' development of mathematical knowledge for teaching, there is thus a dual relationship between the MKT framework and the use of history and original sources in teacher training, which deserves to be investigated further (Jankvist et al. 2012).

27.7.3 Interdisciplinarity and Original Sources

The example of van Maanen's activity of students' reading Bartolus of Saxoferrato also indicates an important role for primary original sources, namely, that of providing a natural environment for *interdisciplinary teaching and learning*. Over the past decades, interdisciplinarity in both research and education has become a frequently debated topic. However, it shall be my claim that from an educational perspective, interdisciplinarity often presents a didactic dilemma: On the one hand, students are told that interdisciplinary work is extremely important (for various different reasons); on the other hand, the students are often only shown somewhat artificial and situational constructed examples, which make the dimension of interdisciplinarity appear pasted on. But because original sources deal with reality – even if it is a historical one – any given interdisciplinary elements within them are likely to illustrate much better to students the importance of interdisciplinarity in research and society. The example by Kjeldsen and colleagues of students' reading of Bernoulli's work on the catenary is actually also an example of interdisciplinarity between mathematics and physics, since the students had to struggle with "Bernouli's mathematization of the physical description of the catenary" – in fact, the students' purpose of studying these sources was to investigate physics' influence on the development of differential equations (see Kjeldsen and Blomhøj 2012). In short, original sources bring authenticity to the dimension of interdisciplinarity in teaching and learning.

27.7.4 Recruitment, Transition, and Retention: A Triple Aspect of a Potential Role for Original Sources

Just as the role of original sources as a means for authentic interdisciplinarity is as relevant for mathematics as it is for the natural sciences (and engineering), so are the following three possible future roles, on which is speculated. The first of these is the role of original sources in relation to the *recruitment problem.* As we know, in the Western world, we have been experiencing problems with recruiting students for the mathematical sciences. Very often, upper secondary school students do not have an accurate idea of what mathematics is all about, when practiced as a scientific discipline at the tertiary levels, e.g., by pure and applied mathematicians at universities. Students' answers to the question of what professional mathematicians do typically range from having no clue at all to believing that they perform some kind of "clean-up job" consisting in finding "errors" in already existing formulas and proofs, more efficient ways of calculating already known quantities, etc. (Jankvist 2009b, forthcoming). Often such views have to do with the students' impression of mathematics as something a priori given, static and rigid – a belief not unrelated to textbooks' usual presentation of mathematical topics of course; only very few students seem to believe it possible that mathematicians can come up with actual *new* mathematics. Therefore, the students know neither what they accept to study nor what they reject to study, if they choose to engage with mathematics. Studying primary original sources can enlighten the students in this respect.[48]

The second role of original sources is related to the *transition problem* between educational levels. From the design and implementation of the HAPh modules as discussed above (Jankvist 2013) and the projects by Barnett using the same original sources, we can make the observation that choosing original sources presenting novel mathematical ideas can assist in making otherwise complicated mathematical topics more accessible to students. One of the reasons for this is that when stepping into uncharted territory, researchers may be more careful in explaining what they are doing and why, as well as why they are approaching a problem in a certain manner. Boole's text on the *Laws of Thought* is one such original source and Euler's text on the Königsberg bridge problem is certainly another. Thus, my point here is that the use of primary original sources may be seen as a way of dealing with the transition problem between, for example, upper secondary level and undergraduate university level. Because, on the one hand, when upper secondary students are presented with such material, they encounter actual research papers from mathematics and/or science, texts, in which the motivation for this piece of research and/or the application of it is sometimes discussed, and even though this happens in a historical setting, it illustrates the nature of research in academic communities in general. And, on the other hand, if such carefully chosen primary sources presenting novel ideas are used in introductory courses at undergraduate level, they may ease the students into the academic way of thinking and thereby make the transition to university level less "harsh."[49]

The third possible role of original sources which is mentioned has to do with the problem of retaining the students once they have already been recruited and

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[48] In fact, student interview data from the HAPh module study support this claim; students expressed that due to their work with the two HAPh modules and hence their reading of the six original texts, they were able either to select or deselect a future engagement with mathematics and mathematical sciences on a more enlightened basis (Jankvist, preprint).

[49] This was also discussed in Jankvist's presentation "The use of original sources and its possible relation to the transition problem" at Colloque Artigue 2012 in Paris.

undergone transition, i.e., the *retention problem*.[50] The authenticity of the sources is also a key element in relation to this problem, as it was for the problem of interdisciplinarity. Because original sources offer a variety of real-life, that is, non-artificial, applications of various mathematical in-issues, such sources can provide *meaning* for the students in their learning. Although not taken from university level, the following quote from an interview with one of the students in the HAPh modules study illustrates this:

> For me, I personally think that I get much more interested, when I see it all, than if I'm only told that now we are studying vectors and we must learn how to dot these vectors and then we must be able to calculate a length, right. That's all very good, but what am I to use it for? Whereas, when you know about the background, the development up till today, that I think was exciting. Because when we began with the first text [Boole's text], it was kind of like, yeah, that's alright, he can figure out this thing here, and this equals that, I can follow that, and 'white sheep' and so… That was good for starters. Then more is built on top, and all of a sudden we see: Why, it's a [electric] circuit we are doing! You could begin to relate it to your own reality; that is, something you knew already. So, the thing about starting from scratch […] and suddenly seeing it form a whole, what it was used for today – and be able to relate it to something, something you knew about – that I think was way cooler. (Interview with Nikita, November 3rd, 2011, translated from Danish. Quoted from Jankvist 2012b, pp. 139–140)

Recently, Pengelley (2012) and Barnett (2012) have designed entire courses in elementary number theory and abstract algebra, respectively, around the use of original sources only – courses thought possibly to play a role also in terms of retention. But nevertheless, what may be still be needed from an empirical point of view is more quantitative data on the effect and efficacy of using primary original sources, data which can underpin and support the many positive qualitative statements, as, for example, that of Nikita above, which are present in the relatively larger number of qualitative empirical studies available in the field.

27.7.5 Additional and Concluding Remarks

In the present chapter, not much effort has been taken to distinguish between using original sources at the various educational levels, except from choosing the illustrative examples to more or less cover the possible spectra. When actually choosing which sources to use in a given situation, the educational level is of course essential, because as Jahnke et al. (2000) point out:

> Incorporating primary sources is not good or bad in itself. We need to establish the aims, including the target population, the kind of source that might be suitable and the didactical methodology necessary to support its incorporation. (Jahnke et al. 2000, p. 293)

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[50] This role of original sources was suggested by David Pengelley, who discussed it during the panel "Empirical research on history in mathematics education: current and future challenges for our field" at HPM2012 in Deajeon.

Also, not much emphasis has been put on the use of original sources in teacher education, except when referring to the study of Clark (2012). However, based on what has been said and discussed, it is possible to provide some comments to at least four of the five questions for future research on the use of original sources formulated by Furinghetti et al. (2006) (cf. Sect. 27.2). Regarding question 1, it seems clear to me that if a use of primary original sources is to gain any real impact in the field of mathematics education, then the evaluation of such uses must build and rely on theoretical constructs and frameworks from mathematics education research. Some examples of such potentially relevant frameworks have been put forth in this chapter (e.g., Ball et al. 2008; Niss and Højgaard 2011; Sfard 2008), but clearly it is possible to find many more that applies in one way or another. As for question 2, it appears that some kind of guidance of the students is a characteristic of many viable approaches for using original sources, whether this is in the form of guided readings, familiarizing the students with the mathematical in-issues before reading a source, as done in the hermeneutic approach, or structuring students' discussions of meta-issues through a use of essay assignments. In terms of question 4, we have seen that a historical research stance, such as the multiple-perspective approach as described by Kjeldsen, indeed can support the use of original sources in the teaching and learning of mathematics. As one of the working tools of this approach, we saw that the notion of epistemic objects and techniques can assist in anchoring students' discussions of meta-issues in the related in-issues (e.g., Jankvist 2009b). Also, the notion of Whig history helped in qualifying our discussion of the various approaches to using original sources. Although question 5 makes up an interesting question, I am not aware of any examples of mathematics education having supported or broadened research in the field of history of mathematics. What is more common is that people in mathematics education, who have taught using original sources, may eventually be drawn towards doing some research in the history of mathematics. Regarding question 3 on the actual impact of the various viable approaches to students' learning and understanding of mathematics, the account given above illustrates that this is not simply a matter of getting students to learn and understand mathematical in-issues or motivate them to do so. Even though this may be the overall end goal, there are other crops to be harvested from using primary original sources, for example, the development of students' mathematical competencies and the development of their overview and judgment. And as mentioned, the development of mathematical competencies may be a much more natural way of assessing the efficiency and efficacy of using history and original sources in mathematics education (Jankvist and Kjeldsen 2011). As for potential crops to be harvested in the future field of using primary original sources, the aforementioned educational problems of interdisciplinarity, recruitment, transition, and retention make up interesting and promising research areas. Already, these problems have the attention of educational researchers, curriculum designers, and policy makers, so if positive empirical results (quantitative and qualitative) could be produced in support of these roles of primary original sources, then surely this would assist in the use of original sources gaining impact in mathematics education in general – and science education too, since these four problems are not restricted to mathematics education alone.

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Part IX
Theoretical Studies: Features of Science and Education

Chapter 28
Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases

Derek Hodson

28.1 Introduction

Before proceeding to the substance of this chapter, it is important to clarify what I mean by *nature of science* (NOS) and note the ways in which I use the term differently from some others. A number of authors seek to restrict its use to the characteristics of scientific knowledge (i.e. to epistemological considerations) and to exclude consideration of the nature of scientific inquiry.[1] This might strike some as an odd decision, given that much of our scientific knowledge and, therefore, consideration of its status, validity and reliability is intimately bound up with the design, conduct and reporting of scientific investigations. Moreover, teaching activities focused on NOS often include empirical investigations and/or critical scrutiny of existing data. Thus, as Ryder (2009) points out, the conduct of scientific inquiry and epistemological considerations are related conceptually, procedurally and pedagogically. Lederman (2006) has acknowledged that 'the phrase 'nature of science' has caused the confusion and the phrase 'nature of scientific knowledge' might be more accurate. The conflation of NOS and scientific inquiry has plagued research on NOS from the beginning' (p. 2). In other words, it would be less confusing to readers if authors used the term 'nature of scientific knowledge (NOSK)' when referring to strictly and/or solely epistemological matters. In common with

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[1] Abd-El-Khalick (2001, 2004, 2005), Abd-El-Khalick and Akerson (2004, 2009), Abd-El-Khalick et al. (1998, 2008), Bell (2004), Flick and Lederman (2004), Hanuscin et al. (2006), Khishfe and Abd-El-Khalick (2002), Khishfe and Lederman (2006, 2007), Lederman (2006, 2007), Lederman and Abd-El-Khalick (1998), Lederman et al. (2001, 2002).

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several other recent publications,[2] the definition of NOS deployed in this chapter encompasses the characteristics of scientific inquiry; the role and status of the scientific knowledge it generates; the modelling that attends the construction of scientific theories; the social and intellectual circumstances of their development; how scientists work as a social group; the linguistic conventions for reporting, scrutinizing and validating knowledge claims; and the ways in which science impacts and is impacted by the social context in which it is located.

Given this much broader definition of NOS, it is quickly apparent that arguments for including NOS in the science curriculum have a long and chequered history. The long-standing tradition of concern for 'the public understanding of science' in the United Kingdom, encompassing much of what I refer to as NOS, dates back to the early years of the nineteenth century. As Jenkins (1990) notes, science was vigorously promoted through the activities of the numerous Mechanics' Institutes and Literary and Philosophical Societies and further supported by public lectures, scientific demonstrations and 'a remarkable variety of books, journals, tracts, pamphlets and magazines, many of which would be categorized today as 'teach yourself publications" (p. 43). Perhaps the earliest proposal for an NOS-oriented curriculum at the school level was Henry Armstrong's heuristic approach,[3] published in 1898, although it is important to note that Armstrong's interest in NOS was mainly pedagogical and motivational; the real purpose was to acquire and develop scientific knowledge. In contrast, John Dewey (1916) argued that familiarity with scientific method was substantially more important than acquisition of scientific knowledge, particularly for those who do not intend to study science at an advanced level. Similarly, Frederick Westaway (1929), an influential HM Inspector of Schools in the United Kingdom in the 1920s, made a strong case for a curriculum focus on NOS:

> Now that science enters so widely and so intimately into every department of life, especially in all questions relating to health and well-being, it is important that the community should have a general knowledge of its *scope and aims*. (p. 9, emphasis added)

Some years later, similar rhetoric formed the basis of Joseph Schwab's (1962) advocacy of a shift of emphasis for school science education in the United States away from the learning of scientific knowledge (the products of science) towards an understanding of the processes of scientific inquiry and the structure of scientific knowledge – a line of argument that eventually led to a string of innovative curriculum projects (PSSC, BSCS, CHEM Study, CBA, ECSP, etc.). NOS-oriented developments in the United Kingdom during the 1960s included the Nuffield Science Projects (with their emphasis on 'being a scientist for the day' and 'developing a proper attitude to theory') and the Schools Council Integrated Science Project (SCISP). However, as a direct consequence of their reliance on an impractical pedagogy

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[2] Allchin (2011), Bartholomew et al. (2004), Clough (2006, 2011), Clough and Olson (2008), Elby and Hammer (2001), Hodson (2008, 2009, 2011), Kelly (2008), Matthews (2012), Osborne et al. (2003), Rudolph (2000), van Dijk (2011), and Wong and Hodson (2009, 2010).

[3] See Brock (1973), Jenkins (1979), Layton (1973) and van Praagh (1973).

of discovery learning and the naïve inductivist model of science underpinning it, these somewhat elitist courses failed to deliver on their rhetoric and promise. Those of us who were required to adopt the pedagogy of discovery learning during its heyday in the 1960s will vividly recall the frustrations of not being allowed to provide students with any guidance or suggest alternative lines of approach when investigating phenomena and events.[4] Subsequently attention shifted towards the so-called process approaches to science education, exemplified by *Warwick Process Science* (Screen 1986, 1988), *Science in Process* (ILEA 1987) and *Active Science* (Coles et al. 1988), which envisaged scientific inquiry as the application of a generalized, all-purpose algorithmic method. A similar shift occurred in Australia, with the publication of the *Australian Science Education Project* (ASEP 1974), and in the United States, with initiatives such as *Science-A Process Approach* (AAAS 1967) being developed on the basis of Robert Gagné's (1963) claim to have identified thirteen basic skills of scientific inquiry.

After a period of decline, interest in NOS underwent a remarkable revival in the decade and a half between 1977 and 1992, with the publication of a number of opinion pieces and commissioned reports,[5] the establishment of the International History, Philosophy and Science Teaching Group (1987) and the first of the now biennial IHPST conferences in Tallahassee in 1987 – developments that led, through the prodigious efforts of Michael Matthews, to the foundation in 1992 of *Science & Education*, the first journal devoted primarily to NOS issues in education. Of particular significance during this period was the incorporation of NOS as a key component in the National Curriculum for England and Wales, established in 1989 following the Education Reform Act of 1988. Another landmark was the publication of Matthews' book *Science Teaching: The Role of History and Philosophy of Science* (Matthews 1994).

Although there has been continuing controversy about what the NOS component of the curriculum should comprise and how it should be implemented (Donnelly 2001), the overall curricular importance of NOS understanding per se is no longer in dispute. Indeed, it has been subsumed within the wider discussion of scientific literacy,

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[4] For example, early on in the original *Nuffield Physics* course, students are provided with a lever, a fulcrum and some weights (uniform square metal plates) and are invited to 'explore' and to 'find out what you can'. No particular problem is stated; no procedure is recommended. It is assumed that the Law of Moments will simply emerge from undirected, open-ended exploration. Nothing could be further from the truth. First, the system does not balance in the way the students expect because the pivot is below the centre of gravity. If the weights are suspended *below* the pivot, as in a set of scales, the beam will balance. However, there is little chance that children will discover this for themselves. Second, children tend to spread the weights irregularly along the entire length of the beam. The complexity of this arrangement obscures the simple relationship that is sought. Consequently, teachers begin to proffer advice on how to make the problem simpler and to issue instructions about the best way to proceed. Similar things happen whenever children are presented with this kind of open-ended situation. See Hodson (1996) for an extended discussion of these issues.

[5] See, for example, Cawthron and Rowell (1978), Hodson (1985, 1986, 1988a, b, 1990, 1991), Matthews (1991, 1992), Nadeau and Désautels (1984)) and Royal Society (1985).

a term that first appeared in the US educational literature about 50 years ago in papers by Paul Hurd (1958) and Richard McCurdy (1958) and in the Rockefeller Brothers Fund (1958) report *The Pursuit of Excellence*, and is now regarded as a key feature of most science curricula.

Despite the term scientific literacy being enthusiastically adopted by many science educators as a useful slogan or rallying call (see Roberts 1983, 2007), there was little in the way of precise or agreed meaning until Pella et al. (1966) suggested that it comprises an understanding of the basic concepts of science, the nature of science, the ethics that control scientists in their work, the interrelationships of science and society, the interrelationships of science and the humanities and the differences between science and technology. Almost a quarter century later, the authors of *Science for All Americans* (AAAS 1989) drew upon very similar categories to define a scientifically literate person as ‘one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes’ (p. 4). It is significant that these perspectives are now an integral part of the US *National Science Education Standards* (National Research Council 1996) and a central plank of the framework for the *Programme for International Student Assessment* (PISA) studies (OECD 1999, 2006, www.pisa.oecd.org). Detailed review of the literature focused on defining notions of scientific literacy is outside the scope of this chapter,[6] save to note that elements of the history of science, philosophy of science and sociology of science that constitute a satisfactory understanding of the nature of science (NOS) have now become firmly established as a major component of scientific literacy and an important learning objective of science curricula in many countries.[7] Indeed, the promotion of NOS in official curriculum documents has become so prominent that Dagher and BouJaoude (2005) have stated: ‘improving students’ and teachers’ understanding of the nature of science has shifted from a *desirable* goal to being a *central* one for achieving scientific literacy’ (p. 378, emphasis added). It follows that all arguments for scientific literacy become arguments for NOS.

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[6] Extensive discussion of the history and evolving definition of scientific literacy can be found in Bybee (1997a, b); Choi et al. (2011), De Boer (2001), Dillon (2009), Feinstein (2011), Gräber and Bolte (1997), Hodson (2008, 2011), Hurd (1998), Laugksch (2000), Lehrer and Schauble (2006), Lemke (2004), Linder et al. (2012), McEneaney (2003), Miller (2000), Norris and Phillips (2003), Norris et al. (2013), Oliver et al. (2001), Roberts (2007), Roth and Calabrese Barton (2004), and Ryder (2001). Teachers’ understanding of scientific literacy is explored by Smith et al. (2012).

[7] For example, AAAS (1993), Council of Ministers of Education (1997), Department of Education (RSA) (2002), Goodrum et al. (2000), Millar and Osborne (1998), National Research Council (1996), Organization for Economic Cooperation and Development (1999, 2003), Osborne and Dillon (2008), and UNESCO (1993).

28.2 Arguments for NOS/Scientific Literacy in the School Science Curriculum

Reviewing what they describe as an extensive and diverse literature, Thomas and Durant (1987) identify three major categories of argument for promoting scientific literacy (and, therefore, aspects of NOS understanding): (i) benefits to science, (ii) benefits to individuals and (iii) benefits to society as a whole. Driver and colleagues (1996) contend that in addition to its intrinsic value, NOS understanding enhances learning of science content, generates interest in science and develops students' ability to make informed decisions on socioscientific issues based on careful consideration of evidence, while Erduran and colleagues (2007) argue that NOS knowledge (and the wider HPS understanding subsumed in the notion of scientific literacy) is of immense value to teachers, making them more reflective and more resourceful.

Benefits to science are seen largely in terms of increased numbers of recruits to science-based professions (including medicine and engineering), greater support for scientific, technological and medical research and more realistic public expectations of science. A related argument is that confidence and trust in scientists depend on citizens having some general understanding of what scientists do and how they do it – in particular, about what they choose to investigate, the methods they employ, how they validate their research findings and theoretical conclusions and where, how and to whom they disseminate their work.

Arguments that scientific literacy brings benefits to *individuals* come in a variety of forms. First, it is commonly argued that scientifically literate individuals will have access to a wide range of employment opportunities and are well positioned to respond positively and competently to the introduction of new technologies in the workplace. Second, it is widely assumed that those who are scientifically literate are better able to cope with the demands of everyday life in an increasingly technology-dominated society, better positioned to evaluate and respond appropriately to the scientific evidence and arguments (sometimes authentic and relevant, sometimes biased, distorted, fallacious or irrelevant) used by advertizing agencies and deployed by politicians and better equipped to make important decisions that affect their health, security and economic well-being.

Arguments that enhanced scientific literacy brings benefits to *society as a whole* include the familiar and increasingly pervasive economic argument and the claim that it promotes democracy and responsible citizenship. The first argument sees scientific literacy as a form of human capital that builds, sustains and develops the economic well-being of a nation. Put simply, continued economic development brought about by enhanced competitiveness in international markets (regarded as incontrovertibly a 'good thing') depends on science-based research and development, technological innovation and a steady supply of scientists, engineers and technicians. The case for scientific literacy as a means of enhancing democracy and responsible citizenship is just as strongly made as the economic argument, though by a very different assembly of stakeholders and interest groups. In the words of Chen and Novick (1984), enhanced scientific literacy (and its attendant components of NOS understanding) is a means 'to avert the situation where social values, individual involvement, responsibility, community participation and the very heart of democratic decision making will be dominated and practiced by a small elite' (p. 425).

This line of argument maintains that democracy is strengthened when *all* citizens are equipped to confront and evaluate socioscientific issues (SSI) knowledgeably and rationally, as well as emotionally, and are enabled to make informed decisions on matters of personal and public concern. Those who are scientifically illiterate are in many ways disempowered and excluded from active civic participation. For these reasons, Tate (2001) declares that access to high-quality science education, with its increasing emphasis on NOS, is a civil rights issue. Of course, as both Levinson (2010) and Tytler (2007) remind us, the notion of science education for citizenship raises a whole raft of questions about the kind of citizen and the kind of society we have in mind and about what constitutes *informed* and *responsible* citizenship – matters well outside the scope of this chapter.

A number of writers have claimed, somewhat extravagantly, that appreciation of the ethical standards and code of responsible behaviour that the scientific community seeks to impose on practitioners will lead to more ethical behaviour in the wider community – that is, the pursuit of scientific truth regardless of personal interests, ambitions and prejudice (part of the traditional image of the objective and dispassionate scientist) makes science a powerful carrier of moral values and ethical principles: 'Science is in many respects the systematic application of some highly regarded human values – integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination' (AAAS 1989, p. 201). Shortland (1988) summarizes this rationale as follows: 'the internal norms or values of science are so far above those of everyday life that their transfer into a wider culture would signal a major advance in human civilization' (p. 310). The authors of *Science for All Americans* (AAAS 1989) present a similar argument: 'Science is in many respects the systematic application of some highly regarded human values – integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination' (p. 201). Studying science, scientists and scientific practice will, they argue, help to instill these values in students. In other words, scientific literacy doesn't just result in more skilled and more knowledgeable people, it results in *wiser* people, that is, people well-equipped to make morally and ethically superior decisions. Whether contemporary scientific practice does impose and instill these values is discussed later in the chapter.

28.3 Establishing NOS Priorities

Once the lens of NOS became focused on the school science curriculum, it was quickly apparent that whatever confused and confusing views of science are held by students are compounded by conventional science education. There are particularly powerful messages about science embedded in all teaching and learning activities, especially laboratory activities. These messages too often convey distorted or over-simplified views of the nature of scientific investigations, especially with respect to the role of theory. These 'folk theories' of science, as Windschitl (2004) calls them, are also held by teachers (as a consequence of their own science education) and have substantial influence on their day-to-day curriculum decision-making, thus reinforcing similar messages embedded in school science textbooks and other curriculum materials.

As part of a major survey of Canadian science education conducted by the Science Council of Canada, Nadeau and Désautels (1984) identified what they called five mythical values stances suffusing science education:

- *Naïve realism* – science gives access to truth about the universe.
- *Blissful empiricism* – science is the meticulous, orderly and exhaustive gathering of data.
- *Credulous experimentation* – experiments can conclusively verify hypotheses.
- *Excessive rationalism* – science proceeds solely by logic and rational appraisal.
- *Blind idealism* – scientists are completely disinterested, objective beings.

The cumulative message is that science has an all-purpose, straightforward and reliable method of ascertaining the truth about the universe, with the certainty of scientific knowledge being located in objective observation, extensive data collection and experimental verification. Moreover, scientists are rational, logical, open-minded and intellectually honest people who are required, by their commitment to the scientific enterprise, to adopt a disinterested, value-free and analytical stance. In Cawthron and Rowell's (1978) words, the scientist is regarded by the science curriculum as 'a depersonalized and idealized seeker after truth, painstakingly pushing back the curtains which obscure objective reality, and abstracting order from the flux, an order which is directly revealable to him through a distinctive scientific method' (p. 32). While much has changed in the intervening years, many school science curricula and school textbooks continue to project these images.[8] For example, Loving (1997) laments that all too often

> (a) science is taught totally ignoring what it took to get to the explanations we are learning – often with lectures, reading text, and memorizing for a test. In other words, it is taught free of history, free of philosophy, and in its final form. (b) Science is taught as having one method that all scientists follow step-by-step. (c) Science is taught as if explanations are the truth – with little equivocation. (d) Laboratory experiences are designed as recipes with one right answer. Finally, (e) scientists are portrayed as somehow free from human foibles, humor, or any interests other than their work. (p. 443)

At about the same time, Hodson (1998) identified ten common myths and falsehoods promoted, sometimes explicitly and sometimes implicitly, by the science curriculum: observation provides direct and reliable access to secure knowledge;

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[8] Abd-El-Khalick (2001), Abd-El-Khalick et al. (2008), Clough (2006), Cross (1995), Knain (2001), Kosso (2009), Lakin and Wellington (1994), McComas (1998), van Eijck and Roth (2008) and Vesterinen et al. (2011).

science always starts with observation; science always proceeds by induction; science comprises discrete, generic processes; experiments are decisive; scientific inquiry is a simple algorithmic procedure; science is a value-free activity; science is an exclusively Western, post-Renaissance activity; the so-called scientific attitudes are essential to the effective practice of science; and all scientists possess these attitudes. A broadly similar list of falsehoods was generated by McComas (1998) from his critical reading of science textbooks: hypotheses become theories that in turn become laws; scientific laws and other such ideas are absolute; a hypothesis is an educated guess; a general and universal scientific method exists; evidence accumulated carefully will result in sure knowledge; science and its methods provide absolute proof; science is procedural more than creative; science and its methods can answer all questions; scientists are particularly objective; experiments are the principal route to scientific knowledge; scientific conclusions are reviewed for accuracy; acceptance of new scientific knowledge is straightforward; science models represent reality; science and technology are identical; and science is a solitary pursuit. In quite startling contrast, Siegel (1991) states that

> Contemporary research… has revealed a more accurate picture of the scientist as one who is driven by prior convictions and commitments; who is guided by group loyalties and sometimes petty personal squabbles; who is frequently quite unable to recognize evidence for what it is; and whose personal career motivations give the lie to the idea that the scientist yearns only or even mainly for the truth. (p. 45)

Two questions spring to mind. First, is this a more authentic portrayal of scientific practice? Second, is it an appropriate view for the school science curriculum? Sweeping away an old and (for some) discredited view is one thing; finding an acceptable set of alternatives is somewhat different. Finding a list appropriate for the school curriculum is even more difficult. Many science educators will share Israel Scheffler's alarm at some of the alternatives that have been advanced:

> The extreme alternative that threatens is the view that theory is not controlled by data, but that data are manufactured by theory; that rival hypotheses cannot be rationally evaluated, there being no neutral court of observational appeal nor any shared stock of meanings; that scientific change is a product not of evidential appraisal and logical judgment, but of intuition, persuasion and conversion; that reality does not constrain the thought of the scientist but is rather itself a projection of that thought. (Scheffler 1967, p. v)

Longbottom and Butler (1999) express similar concerns when they state that 'if we go along with those who deny that modern science provides a privileged view of the world… we fall into an abyss where skeptical postmodernists, who have lost faith in reason, dismiss all knowledge claims as equally arbitrary and assume the universe to be unreliable in its behavior and incapable of being understood' (p. 482). Stanley and Brickhouse (1995) regard such remarks as examples of what Bernstein (1983) called 'Cartesian anxiety': the fear that if we do not retain our belief in the traditional objective foundations of scientific method we have no rational basis for making any knowledge claims. In short, fear that belief in scientific *progress* will be replaced by scientific *change* consequent upon power struggles among competing groups, with 'victory' always going to the better resourced. Fear that scientific knowledge is no longer to be regarded as the product of a rigorous method or set of methods; instead, it is merely the way a particular influential group of scientists happens to think and can persuade, cajole or coerce others into accepting.

In building a school science curriculum, are we faced with a stark choice between the traditional and the postmodern? Are we required to choose between the image of a scientist as a cool, detached seeker-after-truth patiently collecting data from which conclusions will eventually be drawn, when all the evidence is in hand, and that of 'an agile opportunist who will switch research tactics, and perhaps even her entire agenda, as the situation requires' (Fuller 1992, p. 401). Which view is the more authentic? Equally important, what should we tell students? What is in their interests? Some years ago, Stephen Brush (1974) posed the question: 'should the history of science should be rated X?' The question is just as pertinent to the philosophy of science and the sociology of science. Should we expose students to the anarchistic epistemology of Paul Feyerabend? Should we lift the lid off the Pandora's Box that is the sociology of science? Would students be harmed by too early an exposure to these views? When we seek to question (and possibly reject) the certainties of the traditional view of science, are we left with no firm guidance, no standards and no shared meaning? Does recognition of the sociocultural baggage of science entail regarding science as just one cultural artefact among many others, with no particular claim on our allegiance? Is any kind of compromise possible between these extremes and among this diversity? Can we retain what is still good and useful about the old view of science (such as conceptual clarity and stringent testing) while embracing what is good and useful in the new (such as sensitivity to sociocultural dynamics and awareness of the possibility of error, bias, fraud and the misuse of science)? Can the curriculum achieve a balance that is acceptable to most stakeholders? In short, what particular items from all the argument and counter argument would constitute an educationally appropriate and teachable selection? Later discussion touches on the age appropriateness of a number of NOS items, while attention at this point focuses on whether there is any nature of science understanding that can be taken for granted and regarded as no longer in dispute. Is there any consensus among scholars about an acceptable alternative to the traditional view that will allay the fears expressed by Scheffler and others?

Responses to a 20-item Likert-type questionnaire on '15 tenets of NOS' led Alters (1997a, b) to conclude that *there is no consensus* – at least, not among the 210 philosophers of science he surveyed. In the words of Laudan and colleagues (1986),

> The fact of the matter is that we have no well-confirmed general picture of how science works, no theory of science worthy of general assent. We did once have a well developed and historically influential philosophical position, that of positivism or logical empiricism, which has by now been effectively refuted. We have a number of recent theories of science which, while stimulating much interest, have hardly been tested at all. And we have specific hypotheses about various cognitive aspects of science, which are widely discussed but wholly undecided. If any extant position does provide a viable understanding of how science operates, we are far from being able to identify which it is. (p. 142)

Interestingly, despite this categorical denial of any consensus, it seems that the authors of several important science curriculum reform documents (AAAS (1989, 1993) and NRC (1996), among others) seem to be in fairly substantial agreement on the elements of NOS that should be included in the school science curriculum (McComas and Olson 1998):

- Scientific knowledge is tentative.
- Science relies on empirical evidence.
- Observation is theory laden.
- There is no universal scientific method.
- Laws and theories serve different roles in science.
- Scientists require replicability and truthful reporting.
- Science is an attempt to explain natural phenomena.
- Scientists are creative.
- Science is part of social tradition.
- Science has played an important role in technology.
- Scientific ideas have been affected by their social and historical milieu.
- Changes in science occur gradually.
- Science has global implications.
- New knowledge must be reported clearly and openly.

In an effort to shed further light on this matter, Osborne and colleagues (2003) conducted a Delphi study to ascertain the extent of agreement among 23 participants drawn from the 'expert community' on what ideas about science should be taught in school science. The participants included five scientists, five persons categorized as historians, philosophers and/or sociologists of science, five science educators, four science teachers and four science communicators. Although there was some variation among individuals, there was broad agreement on nine major themes: scientific method and critical testing, scientific creativity, historical development of scientific knowledge, science and questioning, diversity of scientific thinking, analysis and interpretation of data, science and certainty, hypothesis and prediction, and cooperation and collaboration. A comparison of these themes with those distilled from the science education standards documents in McComas and Olson's (1998) study reveals many similarities. A broadly similar but shorter list that has gained considerable currency among science educators can be found in Lederman and colleagues (2002): scientific knowledge is tentative, empirically based, subjective (in the sense of being theory dependent and impacted by the scientists' experiences and values), socioculturally embedded and, in part, the product of human imagination and creativity.

28.4 Some Problems with the Consensus View

Useful as consensus can be in assisting curriculum planning and the design of assessment and evaluation schemes, a number of questions should be asked. For example, is the apparent consensus deliberately pitched at such a trivial level that nobody could possibly quibble with it? Most of the items in the list are not specific to science, either individually or collectively. All human knowledge is tentative;

all forms of knowledge building are creative. This is not to say that these characteristics are not applicable to science; but it is to say that they do not distinguish it from several other human activities. It is the sheer banality and unhelpfulness of some of the items that many teachers find frustrating. For example, statements such as 'science is an attempt to explain natural phenomena' and 'science has played an important role in technology' – items in the consensus list developed by McComas et al. (1998) – do not claim anything particularly insightful or helpful for students trying to understand what science is all about. Of course, some would argue that a list of relatively trivial items is better than no list at all. Perhaps it is, although items in the consensus list can sometimes be very puzzling or even irrelevant to an understanding of scientific practice and the capacity to function as a scientist. For example, several writers who advocate the consensus view also argue that students should understand the functions of and relationships between theories and laws and draw a distinction between observation and inference. Drawing a distinction between laws and theories is certainly not a high priority for practising scientists, as informants in the study conducted by Wong and Hodson (2009) pointed out very clearly. As far as students are concerned, one is led to wonder in what ways knowledge of a supposed difference between a law and a theory would help them to make decisions on where they stand in relation to controversial socioscientific issues.

The naïve proposition that there is a crucial distinction between observation and inference is singularly unhelpful to students trying to make sense of contemporary technology-supported investigative work. Superficially the distinction sounds fine and seems to accord with what we consider to be good practice in scientific inquiry: having respect for the evidence and not claiming more than the data can justify. However, closer examination in the light of the theory-laden nature of scientific observation suggests that the supposed demarcation is not always as clear as some would claim. When a new theory appears or when new scientific instruments are developed, our notion of what counts as an observation and what counts as an inference may change. As Feyerabend (1962) points out, observation statements are merely those statements about phenomena and events to which we can assent quickly, relatively reliably and without calculation or further inference because we all accept, without question, the theories on which they are based. Thus, where individuals draw the line between observation and inference reflects the sophistication of their scientific knowledge, their confidence in that knowledge and their experience and familiarity with the phenomena or events being studied. When theories are not in dispute, when they are well understood and taken for granted, the theoretical language *is* the observation language, and we use theoretical terms in making and reporting observations. Terms like *reflection* and *refraction*, *conduction* and *nonconduction*, and *melting, dissolving* and *subliming*, all of which are used regularly in school science as observation terms, carry a substantial inferential component rooted in theoretical understanding. The key point is that unless some theories are taken for granted (and deemed to be no longer in dispute) and unless theory-loaded terms are used for making observations, we can never make progress. We would forever be trying to retreat to the raw data, to some position that we could regard as theory-free.

Too literal an interpretation of statements about the tentative nature of science can be counterproductive, leading students to regard *all* science as no more than temporary (Harding and Hare 2000). Scientific knowledge is tentative because it is based, ultimately, on empirical evidence that may be incomplete and because it is collected and interpreted in terms of current theory – theory that may eventually be changed as a consequence of the very evidence that is collected. In all these endeavours, the creative imagination of individual scientists is impacted by all manner of personal experiences and values. Moreover, the collective wisdom of the scientific community that supports the practice, scrutinizes the procedures and evaluates the products is also subject to complex sociopolitical, economic and moral-ethical forces. In consequence, there can be no certainty about the knowledge produced. However, to admit that absolute truth is an impossible goal is not to admit that we are uncertain about everything. We *know* many things about the universe even though we recognize that many of our theoretical systems are still subject to revision, or even rejection.

Regarding the issue of tentativeness, there are several closely related issues to consider. First, very specific claims about phenomena and events may be regarded as 'true' (in a scientific sense) even though the theories that account for the events are regarded as tentative. Because the whole necessarily extends beyond the parts of which it is comprised, the whole may be seen as tentative while the parts (or some of them) are regarded as certain. Most theories are tentative when first developed, but are accepted as true when they have been elaborated, refined and successfully used and when they are consistent with other theories and strongly supported by evidence. Teachers make a grave mistake when they encourage students to regard all science as tentative. Indeed, if scientists did not accept some knowledge as well established, we would be unable to make progress.

We should also ask whether the consensus list includes consideration of the 'big issues' with which philosophers of science have traditionally grappled. Apparently not, according to Abd-El-Khalick and BouJaoude (1997), Abd-El-Khalick, Bell and Lederman (1998) and Lederman et al. (2002), who state that while philosophers and sociologists might disagree on some aspects of NOS, these disagreements are irrelevant to K-12 students and their teachers. Many other scholars would disagree. Some of these disputes focus on the most interesting features of science, for example, the status of scientific knowledge in terms of realism and instrumentalism, the extent to which science is socially constructed/determined and the nature of scientific rationality. Another major concern with the consensus view is that it promotes a static picture of science and fails to acknowledge important differences among the sciences. In reality, the practices and procedures of science change over time. As a particular science progresses and new theories and procedures are developed, the nature of scientific reasoning changes. Indeed, we should seriously question whether views in the philosophy of science that were arrived at some years ago can any longer reflect the nature of twenty-first-century science, especially in rapidly developing fields such as genetics and molecular biology, where there is now substantial research related to the generation of data and subsequent data mining (e.g. generation of genomic sequences of a number of living things) rather than the kind of hypothesis-driven inquiry promoted by the consensus view – developments that are, of course, driven by technological advances.

In a little known but very insightful and educationally significant article, Michael Clough (2007) urges teachers to shift emphasis away from teaching the 'tenets of NOS', because they are easily misinterpreted, oversimplified and become something to be memorized rather than understood and utilized, and towards asking important questions such as the following: In what sense is scientific knowledge tentative and in what sense is it durable? To what extent is scientific knowledge socially and culturally embedded? In what sense does it transcend society and culture? How are observations and inferences different? In what sense can they not be differentiated? A recent essay by Michael Matthews (2012) subjects the consensus view (specifically, the 'Lederman Seven', as he calls it) to rigorous critical scrutiny, concluding that the items need to be 'much more philosophically and historically refined and developed' (p. 12) if they are to be genuinely useful to teachers and their students. As a way forward, he advocates a shift of terminology and research focus from the 'essentialist and epistemologically focussed 'Nature of Science' (NOS) to a more relaxed, contextual and heterogeneous 'Features of Science' (FOS)' (p. 4). Such a change, he argues, would avoid many of the pitfalls and shortcomings of current research and scholarship in the field – in particular, the confused conflation of epistemological, sociological, psychological, ethical, commercial and philosophical aspects of science into a single list of items to be taught and assessed, the avoidance of debate about contentious issues in HPS, the neglect of historical perspective and the failure to account for significant differences in approach among the sciences. In response to this and other criticism, Lederman, Antinck and Bartos (2012) state 'We (my colleagues and fellow researchers) *are not* advocating a definitive or universal definition of the construct [of NOS]. We have never advocated that that our "list" is *the* only list/definition… What we prefer readers to focus on are the understandings we want students to have. The understandings need not be limited to those we have selected' (p. 2).

28.5 Diversity Among the Sciences

Many philosophers of science hold that there is no universal nature of science because the sciences themselves have no unity. The best that can be said is that there is a 'family resemblance among the sciences' (Wittgenstein 1953), with common interests and some areas of methodological and conceptual agreement – what Loving (1997) calls a 'loose configuration of critical processes and conceptual frameworks, including various methods, aims, and theories all designed to shed light on nature' (p. 437). The consensus view specifically disallows consideration of diversity among the sciences and chooses to disregard the substantial differences between the day-to-day activities of palaeontologists and epidemiologists, for example, or between scientists researching in high energy physics and those engaged in molecular biology. There are significant differences among the subdisciplines of science in terms of the kind of research questions asked, the methods and technologies employed to answer them, the kind of evidence sought, the extent to which they use experimentation, the ways in which data for theory building are collected, the standards by which investigations and conclusions are judged and the kinds of arguments deployed. Jenkins (2007) puts it succinctly when he says that 'the criteria for deciding what counts as evidence, and thus the nature of an explanation that relies upon that evidence, may also be different' (p. 225). There are substantial differences in the extent to which mathematics is deployed (Knorr-Cetina 1999), and there may even be differences, as Cartwright (1999) notes, in the values underpinning the enterprise. In other words, the specifics of scientific rationality change between subdisciplines, with each subdiscipline playing the game of science according to its own rules, a view discussed at some length in Hodson (2008, 2009).

Like Sandra Harding (1986), Ernst Mayr (1988, 1997, 2004) has criticized the standard or consensus NOS views promoted in many curriculum documents on grounds that they are nearly always derived from physics. Biology, he argues, is markedly different in many respects, not the least significant of which is that many biological ideas are not subject to the kind of falsificationist scrutiny advocated by Karl Popper (1959) and given such prominence in school science textbooks: 'It is particularly ill-suited for the testing of probabilistic theories, which include most theories in biology… And in fields such as evolutionary biology… it is often very difficult, if not impossible, to decisively falsify an individual theory' (Mayr 1997, p. 49).

The procedures of investigation in a particular subdiscipline of science are deeply grounded in the field's substantive aspects and the specific purposes of the inquiry. For example, while physicists may spend time designing critical experiments to test daring hypotheses, as Popper (1959) states, most chemists are intent on synthesizing new compounds:

> Chemists make molecules. They do other things, to be sure – they study the properties of these molecules; they analyze… they form theories as to why molecules are stable, why they have the shapes or colors that they do; they study mechanisms, trying to find out how molecules react. But at the heart of their science is the molecule that is made, either by a natural process or by a human being. (Hoffmann 1995, p. 95)

Moreover, as a particular science progresses and new theories and procedures are developed, the nature of scientific reasoning may change. Indeed, Mayr (1988, 2004) has distinguished two different fields even within biology: *functional* or mechanistic biology and *evolutionary* biology, distinguished by the type of causation addressed. Functional biology addresses questions of proximate causation; evolutionary biology addresses questions of ultimate causation:

> The functional biologist is vitally concerned with the operation and interaction of structural elements, from molecules up to organs and whole individuals. His ever-repeated question is 'How?'… The evolutionary biologist differs in his method and in the problems in which he is interested. His basic question is 'Why?' (Mayr 1988, p. 25)

In similar vein, Ault (1998) argues that the geosciences are fundamentally historical and interpretive, rather than experimental. The goal of geological inquiry, he argues, is interpretation of geologic phenomena based on observations, carefully warranted inferences and integration or reconciliation of independent lines of inquiry, often conducted in diverse locations. These interpretations result in a description of historical sequences of events, *sometimes* accompanied by a causal model.

Elby and Hammer (2001) argue that the widely adopted consensus list of NOS items is too general and too broad and that it is neither philosophically valid nor productive of good learning of science: ‘a sophisticated epistemology does not consist of blanket generalizations that apply to all knowledge in all disciplines and contexts; it incorporates contextual dependencies and judgments’ (p. 565). Essentially the same point is made by Clough (2006) when he says that ‘while some characteristics [of NOS] are, to an acceptable degree uncontroversial… most are contextual, with important and complex exceptions’ (p. 463). In short, the differences in approach are just too extensive and too significant to be properly accounted for by generic models of inquiry. Instead of trying to find and promote broad generalizations about the nature of science, scientific inquiry and scientific knowledge, a position recently given renewed emphasis by Abd-El-Khalick (2012), teachers should be building an understanding of NOS from examples of the daily practice of diverse groups of scientists engaged in diverse practices and should be creating opportunities for students to experience, explore and discuss the differences in knowledge and its generation across multiple contexts. It is for this reason that NOS-oriented research needs to study the work of scientists active at the frontier of knowledge generation (Schwartz and Lederman 2008; Wong and Hodson 2009, 2010). Student understanding of the complexity and diversity of scientific practice would be immeasurably helped by adoption of the notion of a ‘family resemblance’ among the sciences, as in Irzik and Nola’s (2011) organization of the cognitive aspects of science into four categories: (i) *activities* (planning, conducting and making sense of scientific inquiries), (ii) *aims and values*, (iii) *methodologies and methodological rules*, and (iv) *products* (scientific knowledge) (see also Nola and Irzik 2013). These four categories of cognitive aspects could and perhaps should be extended to accommodate the noncognitive institutional and social norms which are operative within science and influence science (see below).

In brief, it is time to replace the consensus view of NOS, useful though it has been in promoting the establishment of NOS in the school science curriculum, with a philosophically more sophisticated and more authentic views of scientific practice, as advocated by Elby and Hammer (2001), Hodson (2008, 2009), Matthews (2012), Rudolph (2000) and Wong and Hodson (2013). Interestingly, children regard diversity of approach in scientific investigations as inevitable. They have no expectations of a particular method; it is the teachers who create the expectation of a single method through their continual reference to *the* scientific method (Hodson 1998) and, by extension, establish the belief that there are particular and necessary attributes (the so-called scientific attitudes) for engaging in it.

28.6 Some Recent NOS-Oriented Initiatives

The past decade has seen a remarkable growth in research and curriculum development in two important NOS-related areas: *scientific argumentation* and *modelling*. Both these aspects of NOS (as defined at the beginning of this chapter) warrant some attention here. My concerns relate to both students' knowledge of these processes as used by scientists and the development of their ability to use them appropriately and productively for themselves.

What is often unrecognized by science teachers, science textbooks and curricula, and by the wider public, is that *dispute* is one of the key driving forces of science. Real science is impregnated with claims, counter claims, argument and dispute. Arguments concerning the appropriateness of experimental design, the interpretation of evidence and the validity of knowledge claims are located at the core of scientific practice. Arguments are used to address problems, resolve issues and settle disputes. Moreover, our day-to-day decision-making with regard to socioscientific issues is based largely on the evaluation of information, arguments, conclusions, views, opinions and reports made available via newspapers, magazines, television, radio and the Internet. Citizens need to know the kinds of knowledge claims that scientists make and how they advance them. They need to understand the standards, norms and conventions of scientific argumentation in order to judge the rival merits of competing arguments and engage meaningfully in debate on SSI. In particular, they need a robust understanding of the form, structure and language of scientific arguments, the kind of evidence invoked, how it is organized and deployed and the ways in which theory is used and the work of other scientists cited to strengthen a case.

Neglect of scientific argumentation in the school science curriculum gives the impression that science is the unproblematic accumulation of data and theory. In consequence, students are often puzzled and may even be alarmed by reports of disagreements among scientists on matters of contemporary importance. They may be unable to address in a critical and confident way the claims and counter claims impregnating the SSI with which they are confronted in daily life. A number of science educators have recently turned their attention to these matters and to what had previously been a shamefully neglected area of research and curriculum development.[9] The research agenda focuses on the following questions: Why is argumentation important? What are the distinctive features of scientific argumentation? How can it be taught? What strategies are available? To what extent and in what

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[9] For example, Arduriz Bravo (2013), Berland and Hammer (2012), Berland and Lee (2012), Berland and McNeill (2010), Berland and Reiser (2009, 2011), Böttcher and Meisertt (2011), Bricker and Bell (2008), Driver et al. (2000), Duschl (2008), Duschl and Osborne (2002), Erduran et al. (2004), Evagorou and Osborne (2013), Ford and Wargo (2012), Jiménez-Aleixandre and Erduran (2008), Khishfe (2012a), Kuhn (2010), Newton et al. (1999), Nielsen (2012a, b, 2013), Osborne (2001), Osborne and Patterson (2011), Osborne et al. (2004), Passmore and Svoboda (2012), Pluta et al. (2011), Sampson and Clark (2008, 2011), Sampson and Blanchard (2012), Sampson and Walker (2012), Sampson et al. (2011), Sandoval and Cam (2011), Sandoval and Millwood (2005, 2008), Simon et al. (2006), and Ryu and Sandoval (2012)

ways are the strategies successful? What problems arise and how can the difficulties be overcome? This research is discussed at length in Hodson (2009).

Another significant NOS-related growth area in recent years has been the focus on models and modelling. Because scientific literacy entails a robust understanding of a wide range of scientific ideas, principles, models and theories, students need to know something of their origin, scope and limitations; understand the role of models in the design, conduct, interpretation and reporting of scientific investigations; and recognize the ways in which a complex of cognitive problems and factors related to the prevailing sociocultural context influenced the development of key ideas over time. They also need to experience model building for themselves and to give and receive criticism in their own quest for better models. As Matthews (2012) comments, 'It is difficult to think of science without models' (p. 19).

The nature of mental models has long been an area of research in cognitive psychology, dating back to the seminal work of Johnson-Laird (1983) and Gentner and Stevens (1983), but in recent years, the topic of models and modelling has generated considerable interest among science educators.[10] This interest can be categorized into three principal areas of concern: the particular models and theories produced by scientists as explanatory systems, including the history of their development; the ways in which scientists utilize models as cognitive tools in their day-to-day problem solving, theory articulation and theory revision; and the role of models and modelling in science pedagogy.

The emergence of curricula oriented towards the consideration of socioscientific issues (SSI), in which NOS plays a key role, is discussed later in the chapter.

28.7 Assessing NOS Understanding

Given the perennial concern of education policy makers with assessment and accountability measures and the need for teachers to ascertain students' knowledge and understanding both prior to and following instruction, there has been a long-standing interest in researching students' NOS views. Also, given the commonsense understanding that teachers' views will inevitably and profoundly impact the kind of teaching and learning experiences they provide, interest has been high in ascertaining

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[10] Bamberger and Davis (2013), Clement and Rea-Ramirez (2008), Coll (2006), Coll and Taylor (2005), Coll and Treagust (2002, 2003a, b), Coll et al. (2005), Davies and Gilbert (2003), Duschl and Grandy (2008), Erduran and Duschl (2004), Franco et al. (1999), Gilbert (2004), Gilbert and Boulter (1998, 2000), Gilbert et al. (1998a, b), Gobert and Pallant (2004), Gobert et al. (2011), Greca and Moreira (2000, 2002), Halloun (2004, 2007), Hansen et al. (2004), Hart (2008), Justi and Gilbert (2002a, b, c, 2003), Justi and van Driel (2005), Kawasaki et al. (2004), Khan (2007), Koponen (2007), Lehrer and Schauble (2005), Lopes and Costa (2007), Maia and Justi (2009), Manz (2012), Nelson and Davis (2012), Nersessian (2008), Oh and Oh (2011), Perkins and Grotzer (2005), Russ et al. (2008), Saari and Viiri (2003), Shen and Confrey (2007), special issue of *Science & Education* (2007, 16, issues 7–8), Svoboda et al. (2013), Taber (2003), Taylor et al. (2003), Treagust et al. (2002, 2004), and van Driel and Verloop (1999)

teachers' NOS views. Given suitable modification in terms of language and theoretical sophistication, the two tasks can utilize many of the same instruments.

Methods employed include questionnaires and surveys, interviews, small group discussions, writing tasks and classroom observations (particularly in the context of hands-on activities). Each has its strengths and weaknesses. Necessarily, researchers who use questionnaire methods must decide what counts as legitimate research data *before* the data collection process begins; those who use classroom observation (and, to a lesser extent, those who use interview methods) are able to make such decisions *during* or *after* data collection. They also have the luxury of embracing multiple perspectives and can readily update their interpretive frameworks to take account of changes in our understanding in history, philosophy and sociology of science.

More than 30 years ago, a review by Mayer and Richmond (1982) listed 32 NOS-oriented assessment instruments, among the best known of which are the *Test on Understanding Science* (TOUS) (Cooley and Klopfer 1961), the *Nature of Science Scale* (NOSS) (Kimball 1967), the *Nature of Science Test* (NOST) (Billeh and Hasan 1975) and the *Nature of Scientific Knowledge Scale* (NSKS) (Rubba 1976; Rubba and Anderson 1978), together with a modified version (M-NSKS) developed by Meichtry (1992). Instruments dealing with the processes of science, such as the *Science Process Inventory* (SPI) (Welch 1969a), the *Wisconsin Inventory of Science Processes* (WISP) (Welch 1969b) and the *Test of Integrated Process Skills* (TIPS) (Burns et al. 1985; Dillashaw and Okey 1980) could also be regarded as providing valuable information on some key aspects of NOS.

While questionnaires are the most commonly used research methods, largely because they are quick and easy to administer, they can be overly restrictive, incapable of accommodating subtle shades of meaning and susceptible to misinterpretation. Sometimes the complexity and subtlety of NOS issues makes it difficult to find appropriate language for framing questions. If it is difficult for the researcher to find the right words, how much more difficult is it for the respondent to capture the meaning they seek to convey? It cannot be assumed that the question and/or the answer will be understood in exactly the way it was intended, especially by younger students and those with poor language skills. Multiple-choice items and other objective instruments leave little or no scope for expressing doubt or subtle shades of difference in meaning and rarely afford respondents the opportunity to explain *why* they have made a particular response to a questionnaire item. It may even be that the same response from two respondents arises from quite different understanding and reasoning, while similar reasoning by two respondents results in different responses.

Further, many instruments are constructed in accordance with a particular philosophical position and are predicated on the assumption that all scientists think and behave in the same way. Hence, teacher and/or student responses that do not correspond to the model of science assumed in the test are judged to be 'incorrect', 'inadequate' or 'naïve'. Alters (1997a, b), Koulaidis and Ogborn (1995), Lucas (1975) and Lederman et al. (2002) provide extended discussions of this issue. It is also the case that many of the early instruments predated significant work in the philosophy and sociology of science, and so are of severely limited value in contemporary studies. Reviews by Lederman (1992, 2007), Lederman et al. (1998, 2000, 2013) describe several NOS instruments that take into account the work of more recent and even contemporary scholars in the philosophy and sociology of science, including *Conceptions of Scientific Theories Test* (COST) (Cotham and Smith 1981), *Views on Science-Technology-Society* (VOSTS) (Aikenhead et al. 1989), the *Nature of Science Survey* (Lederman and O'Malley 1990), the *Nature of Science Profile* (Nott and Wellington 1993) and the *Views of Nature of Science Questionnaire* (VNOS) (Lederman et al. 2002) and its several subsequent modifications (see Flick and Lederman 2004; Lederman 2004, 2007; Schwartz and Lederman 2008). A recent review by Deng and colleagues (2011) reports and critiques 105 research studies of students' NOS views, using a wide range of instruments, though lack of space precludes discussion here. Constraints on space also preclude discussion of the recent critical review by Guerro-Ramos (2012) of research approaches for ascertaining teachers' views of NOS and their relevance to classroom decision-making.

The designers of VOSTS attempted to circumvent some of the common questionnaire design problems identified by psychometricians by constructing a number of different 'position statements' (sometimes up to ten positions per item) derived from student writing and interviews, including 'I don't understand' and 'I don't know enough about this subject to make a choice' (Aikenhead et al. 1987; Aikenhead and Ryan 1992). It is the avoidance of the forced choice and the wide range of aspects covered (definitions, influence of society on science/technology, influence of science/technology on society, characteristics of scientists, social construction of scientific knowledge, social construction of technology, nature of scientific knowledge, and so on) that give the instrument its enormous research potential. Lederman and O'Malley (1990) utilized some of the design characteristics of VOSTS to develop the *Nature of Science Survey*, an instrument comprising just seven fairly open-ended items (e.g. 'Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer'), to be used in conjunction with follow-up interviews to further explore and clarify students' responses.

At present, the most widely used and most extensively cited contemporary instrument for ascertaining students' NOS views is the *Views of Nature of Science Questionnaire* (VNOS). While it has provided much valuable information on both students' and teachers' NOS views, it suffers from all the drawbacks attending the so-called consensus view of NOS, as discussed earlier. The *Views on Science and Education* (VOSE) questionnaire, developed by Chen (2006) for use with preservice teachers, focuses on the same seven NOS elements as VNOS (tentativeness of scientific knowledge; nature of observation; scientific methods; hypotheses, laws and theories; imagination; validation of scientific knowledge; objectivity and subjectivity in science) but seeks to address some perceived weaknesses of VOSTS – principally, the overgeneralization and ambiguity of some items and its failure to fully ascertain the reasons underlying a respondent's choice of response. It also seeks to accommodate differences in student teachers' views about what science is likely to be in practice and what science ought to be and to distinguish between NOS views they hold and NOS views they seek to teach.

As Abd-El-Khalick and BouJaoude (1997) point out, VOSTS was conceived and written within a North American sociocultural context and, in consequence, may have limited validity in non-Western contexts. In response to such concerns, Tsai and Liu (2005) have developed a survey instrument that is more sensitive to sociocultural influences on science and students' views of science. It focuses on five characteristics of scientific knowledge and its development: (i) the role of social negotiations within the scientific community; (ii) the invented and creative nature of science; (iii) the theory-laden nature of scientific investigation; (iv) cultural influences on science; and (v) the changing and tentative nature of scientific knowledge. Rooted in similar concerns about the socioculturally determined dimensions of NOS understanding is the *Thinking about Science* instrument designed by Cobern and Loving (2002) as both a pedagogical tool (for preservice teacher education programmes) and a research tool for assessing views of science in relation to economics, the environment, religion, aesthetics, race and gender.

Before leaving this brief survey of questionnaire instruments, it is important to draw attention to the *Views of Scientific Inquiry* questionnaire (Schwartz et al. 2008), which speaks directly to the problems of NOS definition discussed at the beginning of this chapter and is designed to gather information on students' understanding of some key elements of NOS, including (i) scientific investigations are guided by questions and theoretical perspectives; (ii) there are multiple purposes for scientific inquiry and multiple methods for conducting them; (iii) there is an important distinction between data and evidence; (iv) the validation of scientific knowledge involves negotiation of meaning and achievement of consensus; and (v) scientific inquiry is embedded within multiple communities, each with its own standards, values and practices.

28.8 Alternatives to Questionnaires

Frustrated by the seemingly intractable problems of designing effective questionnaires, some researchers and teachers incline to the view that more useful information can be obtained, especially from younger students, by use of open-ended methods such as the Draw-a-Scientist Test (DAST) (Chambers 1983). In his initial study, Chambers used this test with 4,807 primary (elementary) school children in Australia, Canada and the United States. He identified seven common features in their drawings, in addition to the almost universal representation of the scientist as a man: laboratory overall; spectacles (glasses); facial hair; 'symbols of research' (specialized instruments and equipment); 'symbols of knowledge' (books, filing cabinets, etc.); technological products (rockets, medicines, machines); and captions such as 'Eureka' (with its attendant lighted bulb) and $E = mc^2$, and think bubbles saying 'I've got it' or 'A-ah! So that's how it is'.

In the years since Chambers' original work, students' drawings have changed very little,[11] with research indicating that the stereotype begins to emerge at about grade 2 and is well-established and held by the majority of students by grade 5.

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[11] Barman (1997, 1999), Farland-Smith (2009a), Finson (2002), Fort and Varney (1989), Fralick et al. (2009), Fung (2002), Huber and Burton (1995), Jackson (1992), Losh et al. (2008), Mason et al. (1991), Matthews (1994a, 1996), Newton and Newton (1992, 1998), Rahm and Charbonneau (1997), Rosenthal (1993), She (1995, 1998), and Symington and Spurling (1990)

Not only are these images stable across genders, they seem to be relatively stable across cultural differences,[12] although Song and Kim (1999) suggest that Korean students produce 'slightly less stereotypical' drawings, especially with respect to gender and age, than students in the United States. Generally, they draw younger scientists than their Western student counterparts – drawings that probably reflect the reality of the Korean scientific community. In a study of 358 students in grades 1–7 in Southwest Louisiana, Sumrall (1995) found that African American students (especially girls) produced less stereotyped drawings than Euro-Americans with respect to both gender and race. Interestingly, the drawings of African American boys showed an equal division of scientists by race but an 84% bias in favour of male scientists. Many researchers have pointed out that girls are generally less stereotyped in their views about science and scientists than are boys. However, Tsai and Liu (2005) note that female Taiwanese students are less receptive than male students to the idea that scientific knowledge is created and tentative rather than discovered and certain. There are some encouraging indications that students, and especially male students in the age range 9–12, produce drawings with fewer stereotypical features following the implementation of gender-inclusive curriculum experiences (Huber and Burton 1995; Losh et al. 2008; Mason et al. 1991).

Of course, there is a strong possibility that researchers can be seriously misled by the drawings students produce. As Newton and Newton (1998) point out, 'their drawings reflect their stage of development and some attributes may have no particular significance for a child but may be given undue significance by an adult interpreting them' (p. 1138). Even though young children invariably draw scientists as bald men with smiling faces, regardless of the specific context in which the scientist is placed, it would be unwise to assume that children view scientists as especially likely to be bald and contented. As Claxton (1990) reminds us, children compartmentalize their knowledge and so may have at least three different versions of the scientist at their disposal: the everyday comic book version, the 'official' or approved version for use in school and their personal (and perhaps private) view. It is not always clear which version DAST is accessing or how seriously the drawer took the task. Simply asking students to 'draw a scientist' might send them a message that a 'typical scientist' exists (Boylan et al. 1992). There is also the possibility that students in upper secondary school or university use their drawings to make a sociopolitical point – for example, that there are too few women or members of ethnic minority groups engaged in science.

Scherz and Oren (2006) argue that asking students to draw the scientist's workplace can be helpful, while Rennie and Jarvis (1995) suggest that students should be encouraged to annotate their drawings in order to clarify meaning and intention. Further insight into students' views can be gained by talking to them about their drawings and the thinking behind them, asking them if they know anyone who uses science in their work (and what this entails), or presenting them with writing tasks based on scientific discovery. Miller (1992, 1993) advocates the

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[12] Chambers (1983), Farland-Smith (2009b), Finson (2002), Fung (2002), Laubach et al. (2012), Parsons (1997), She (1995, 1998), and Walls (2012)

following approach: 'Please tell me, in your own words, what does it mean to study something scientifically?' When given the opportunity to discuss their drawings and stories with the teacher, even very young children will provide detailed explanations and rationales (Sharkawy 2006; Sumrall 1995; Tucker-Raymond and colleagues 2007). Interestingly, it is increasingly evident that young children's responses to open-ended writing tasks involving science, scientists and engineers are not stable and consistent: accounts and stories of science produced in science lessons are very different from those produced in language arts lessons (Hodson 1993). Students may even provide significantly different oral and written responses to nature of science questions (Roth and Roychoudhury 1994).

While less restrictive, instruments designed for more flexible and open-ended responses, such as the *Images of Science Probe* (Driver et al. 1996), concept mapping, small group discussion and situated-inquiry interviews (Ryder et al. 1999; Welzel and Roth 1998), sometimes pose major problems of interpretation for the researcher. So, too, do observation studies, unless supported by an interview-based follow-up capable of exploring the impact of context on student understanding. While interviews hold out the possibility of accessing underlying beliefs, their effectiveness can be severely compromised by the asymmetric power relationship between interviewer and interviewee, regardless of whether the interviewer is the teacher or an independent researcher. In an interview situation, some students may be shy or reluctant to talk; they may feel anxious or afraid; they may respond in ways that they perceive to be acceptable to the interviewer, or expected by them. Observation via audio or video recording of group-based tasks involving reading, writing and talking, practical work, role play, debating and drama constitute a less threatening situation for students, though even here there can be problems. Indeed, any classroom activity can be impacted by complex and sometimes unpredictable social factors. These complicating factors can mask or distort the NOS understanding we hope to infer from conversations and actions. In short, all approaches to ascertaining NOS views carry a risk that the characterization or description of science ascribed to the research subject is, in some measure, an artefact of the research method.

28.9 Problems Relating to Authenticity and Context

The context in which an interview question, questionnaire item or assessment task is set and, indeed, whether there is a specific context at all can have a major impact on an individual's response. Decontextualized questions (such as 'What is your view of a scientific theory?' or 'What is an experiment?') can seem infuriatingly vague to students and can be met with seeming incomprehension. Use of such questions can pose major problems of interpretation for the researcher. Conversely, context-embedded questions have domain-specific knowledge requirements that may sometimes preclude students from formulating a response that properly reflects their NOS views. Moreover, respondents may feel constrained by restriction of the question to one context and, in consequence, unable to communicate what they know about the many significant differences in the ways that scientists in different fields conduct investigations. Familiarity with the context, understanding of the underlying science concepts, interest in the situation and opportunity to utilize knowledge about other situations are all crucial to ensuring that we access students' authentic NOS understanding. Put simply, questions set in one context may trigger different responses from essentially the same questions set in a different context (Leach and colleagues 2000) – a finding that is especially significant in research that addresses NOS views in the context of scientific controversies (Smith and Wenk 2006) and socioscientific issues (Sadler and Zeidler 2004). It should also be noted that further important perspectives and issues relating to assessment are raised by recent curricular interest in scientific argumentation[13] and modelling,[14] though constraints on space preclude discussion here.

It would be surprising if students didn't have different views about the way science is conducted in school and the way science is conducted in specialist research establishments. Hogan (2000) refers to these different views as students' *proximal* knowledge of NOS (personal understanding and beliefs about their own science learning and the scientific knowledge they encounter and develop in science lessons) and *distal* knowledge of NOS (views they hold about the products, practices, codes of behaviour, standards and modes of communication of professional scientists). Sandoval (2005) draws a similar distinction between students' *practical* and *formal* epistemologies. Contextualized questions that ask students to reflect on their own laboratory experiences are likely to elicit the former, questions of a more general, de-contextualized nature ('What is science?' or 'How do scientists validate knowledge claims?') are likely to elicit the latter. The problem for the researcher is to gauge the extent to which these differences exist and how they are accessed by different research probes. The problem for the teacher is to ensure that students are aware of the crucial distinctions as well as the similarities between science in school and science in the world outside school. It may also be the case that students hold significantly different views of science as they perceive it to be and science as they believe it *should* be – a distinction that Rowell and Cawthron (1982) and Chen (2006) were able to accommodate in their research.

A further complication to ascertaining students' NOS views is the significant potential for mismatch between what individuals say about their NOS understanding and what they do in terms of acting on that understanding. Thus, the question arises: Should we seek to ascertain *espoused* views or views *implicit in actions?*

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[13] Important literature sources include Duschl (2008), Erduran (2008), Erduran et al. (2004), Kelly and Takao (2002), Naylor et al. (2007), Osborne et al. (2004), Sampson and Clark (2006, 2008), Sandoval and Millwood (2005), Shwarz et al. (2003), Takao and Kelly (2003), and Zeidler et al. (2003).

[14] Suitable references include Acher et al. (2007), Chittleborough et al. (2005), Coll (2006), Coll and Treagust (2003a), Duschl et al. (2007), Hart (2008a), Henze et al. (2007a, b), Justi and Gilbert (2002a), Justi and van Driel (2005), Kawasaki et al. (2004), Lehrer and Schauble (2000), Lin and Chiu (2007), Maia and Justi (2009), Perkins and Grotzer (2005), Prins et al. (2008), Raghavan et al. (1998a, b), Saari and Viiri (2003), Schauble (2008), Smith et al. (2000), Taylor et al. (2003), Treagust et al. (2002, 2004), van Driel and Verloop (1999), and Webb (1994).

The former would probably be best served by questionnaires, writing tasks and interviews; the latter would require inferences to be drawn from observed behaviours and actions – for example, responding to scientific texts, searching the Internet and formulating reports of investigations. The crucial distinction between *teachers'* NOS views implicit in action and those supposedly revealed by pencil-and-paper tests is explored at length by Guerra-Ramos (2012). Of particular value for use with teachers and student teachers is Nott and Wellington's (1996, 1998, 2000) 'Critical Incidents' approach. In group settings, or in one-on-one interviews, teachers (or student teachers) are invited to respond to descriptions of classroom events, many related to hands-on work in the laboratory, by answering three questions: What would you do? What could you do? What should you do? Responses, and the discussion that ensues, may indicate something about the teachers' views of science and scientific inquiry and, more importantly perhaps, how this understanding is deployed in classroom decision-making. Similar approaches using video and multimedia materials have been used by Bencze and colleagues (2009a), Hewitt and colleagues (2003), Wong and colleagues (2006) and Yung and colleagues (2007).[15]

Even if we solve all these problems, we are still confronted with decisions about how to interpret and report the data. Should we adopt a *nomothetic* approach that focuses on the extent to which the students' or teachers' views match a prespecified 'ideal' or approved view? Attempts to distinguish 'adequate' NOS views from 'inadequate' views involve judgement about the rival merits of inductivism and falsificationism, Kuhnian views versus Popperian views, realism versus instrumentalism, and so on. None of these judgements is easy to make and may even be counterproductive to good NOS learning. Does it make more sense, then, to opt for an *ideographic* approach? Should we be satisfied to describe the views expressed by students and seek to understand them 'on their own terms'?

A major complicating factor is that students will not necessarily have coherent and consistent views across the range of issues embedded in the notion of NOS. Rather, their views may show the influence of several different and possibly mutually incompatible philosophical positions. As Abd-El-Khalick (2004) points out, what researchers see as inconsistencies in the NOS views of students at the undergraduate and graduate levels may be seen by the students as 'a collection of ideas that make sense within a set of varied and personalized images of science' (p. 418). Moreover, older students, with more sophisticated NOS understanding, will have recognized that inquiry methods vary between science disciplines and that the nature of knowledge statements varies substantially with content, context and purpose. Few research instruments are sensitive to such matters. By assigning total scores rather than generating a profile of views, the research conflates valuable data that could inform the design of curriculum interventions.

Rather than assigning individuals to one of several predetermined philosophical positions, it might make more sense to refer to their *Personal Framework of NOS*

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[15] Other important studies of video-based teacher professional development programmes include Borko and colleagues (2008), Rosaen and colleagues (2008), Santagata and colleagues (2007) and Zhang and colleagues (2011).

Understanding and seek to highlight its interesting and significant features, an undertaking that could be facilitated by the use of repertory grids (as in the study by Shapiro 1996).[16] One such recent study by Ibrahim et al. (2009) seeks to consolidate data from a purpose-built questionnaire into NOS profiles. The questionnaire, *Views about Scientific Measureme*nt (VASM), which comprises six items addressing aspects of NOS and eight items dealing with scientific measurement, uses a common context (in earth sciences) and allows space for students to elaborate on their response or compose an alternative. The data, obtained from 179 science undergraduates, were found to cluster into four partially overlapping profiles, which the authors refer to as *modellers*, *experimenters*, *examiners* and *discoverers*. For *modellers*, theories are simple ways of explaining the often complex behaviour of nature; they are constructed by scientists and tested, validated and revised through experimentation. Creativity plays an important role in constructing hypotheses and theories and in experimentation. When there are discrepancies between theoretical and experimental results, both theory and the experimental data need to be scrutinized. *Experimenters* also believe that scientists should use experimental evidence to test hypotheses and theories but should do so in accordance with a strict scientific method. In situations of conflict, data have precedence over theories. *Examiners* regard the laws of nature as fixed and 'out there' waiting to be discovered through observation, rather than constructed by scientists. Experimental work is essential; it is not informed by theory. Scientists may use both the scientific method and their imagination, but experimental data always have precedence over theories. *Discoverers* also believe that the laws of nature are out there waiting to be discovered through observation. Only experiments using the scientific method can be used to generate laws and theories. If experimental data conflict with a previously established theory, then both the theory and the data need to be checked.[17] Profiling could solve many of the problems associated with the compilation and interpretation of data on NOS understanding among both students and teachers.

28.10 Some Current Emphases in NOS-Oriented Curricula

Despite the many caveats concerning the validity and reliability of research methods, it is incumbent on teachers, teacher educators and curriculum developers to pay attention to the rapidly growing number of studies indicating that both students and

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[16] Repertory grids enable researchers to ascertain links between different facets of an individual's knowledge and understanding (and between understanding and actions) in quantitative form (Fransella and Bannister 1977). Using them over the lifetime of a research project enables a developmental record of students' (or teachers') views to be built up. Because repertory grids often produce surprising data and highlight inconsistencies in respondents' views, they provide a fruitful avenue for discussion and exploration of ideas. For these reasons, Pope and Denicolo (1993) urge researchers to use them as 'a procedure that facilitates a conversation' (p. 530).

[17] Interestingly, as a percentage of the total, the modeller profile was more common among students following a 4-year science foundation course than among physics majors.

teachers have inadequate, incomplete or confused NOS understanding.[18] Two points are worth making. First, the goal of improving NOS understanding is often prejudiced by stereotyped images of science and scientists consciously or unconsciously built into school science curricula[19] and perpetuated by science textbooks.[20] This should be a relatively easy problem to fix, and it is fair to say that the situation is not nearly so dire as it was a decade or so ago. Second, research has shown that, in general, an *explicit* approach is much more effective than an *implicit* approach in fostering more sophisticated conceptions of NOS.[21]

In an explicit approach, NOS understanding is regarded as curriculum content, to be approached carefully and systematically, just like any other lesson content. This does not entail a didactic or teacher-centred approach or the imposition of a particular view through exercise of teacher authority, but it does entail rejection of the belief that NOS understanding will just develop in students as a by-product of engaging in other learning activities. Most effective of all are approaches that have a substantial reflective component.[22] Adúriz-Bravo and Izquierdo-Aymerich (2009), Howe and Rudge (2005) and Rudge and Howe (2009) argue that an explicit reflective approach is particularly effective when historical case studies are used to engage students in the kinds of reasoning used by scientists originally struggling to make sense of phenomena and events and to construct satisfactory explanations, while Wong and colleagues (2008, 2009) have shown the value of embedding explicit teaching of NOS within a consideration of important socioscientific issues.

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[18] Abd-El-Khalick and Lederman (2000a, b), Abell and Smith (1994), Aikenhead and Ryan (1992), Akerson and Buzzelli (2007), Akerson and Hanuscin (2007), Akerson et al. (2008), Barman (1997), Apostolou and Koulaidis (2010), Brickhouse et al. (2002), Carey and Smith (1993), Carey et al. (1989), Chambers (1983), Dagher et al. (2004), Dogan and Abd-El-Khalick (2008), Driver et al. (1996), Duveen et al. (1993), Finson (2002, 2003), Fung (2002), Griffiths and Barman (1995), Hodson (1993), Hofer (2000), Hogan and Maglienti (2001), Honda (1994), Irez (2006), Kang et al. (2005), Koren and Bar (2009), Larochelle and Desautels (1991), Leach et al. (1996, 1997), Lederman (1992, 1999), Liu and Lederman (2002, 2007), Liu and Tsai (2008), Lubben and Millar (1996), Lunn (2002), Mbajiorgu and Iloputaife (2001), Meichtry (1992), Meyling (1997), Moseley and Norris (1999), Moss et al. (2001), Palmer and Marra (2004), Parsons (1997), Paulsen and Wells (1998), Rampal (1992), Rubin et al. (2003), Ryan (1987), Ryan and Aikenhead (1992), Ryder et al. (1999), Sandoval and Morrison (2003), Schommer and Walker (1997), She (1995, 1998), Smith and Wenk (2006), Smith et al. (2000), Solomon et al. (1994), Solomon et al. (1996), Song and Kim (1999), Sumrall (1995), Tucker-Raymond et al. (2007), Tytler and Peterson (2004), Vázquez and Manassero (1999), Vázquez et al. (2006), and Windschitl (2004)

[19] Bell et al. (2003), Hodson (1998), and Milne (1998).

[20] Abd-El-Khalick (2001), Abd-El-Khalick et al. (2008), Knain (2001), Kosso (2009), McComas (1998), van Eijck and Roth (2008), and Vesterinen et al. (2011).

[21] Abd-El-Khalick (2001, 2005), Abd-El-Khalick and Lederman (2000a), Akerson and Abd-El-Khalick (2003, 2005), Akerson and Hanuscin (2007), Bell (2004), Bell et al. (2000, 2011), Faikhamta (2012), Hanuscin et al. (2006, 2011), Khishfe (2008), Khishfe and Abd-El-Khalick (2002), Lederman and Abd-El-Khalick (1998), Lin et al. (2012), Morrison et al. (2009), Posnanski (2010), Ryder (2002), Scharmann et al. (2005), Schwartz and Lederman (2002), and Schwartz et al. (2004).

[22] Akerson and Donnelly (2010), Akerson and Volrich (2006), Akerson et al. (2000, 2010), Heap (2006), and Lucas and Roth (1996).

Other notable research studies include the finding by Schwartz et al. (2004) that preservice teachers' NOS understanding was favourably enhanced when their course included a research component and journal-based assignments; the report by Morrison et al. (2009) that substantial gains in NOS understanding are achieved when explicit, reflective instruction in NOS is augmented by opportunities to interview practising scientists about their work and/or undertake some job sharing; and the study by Abd-El-Khalick and Akerson (2009) that notes major gains in the NOS understanding of preservice elementary teachers when explicit, reflective instruction is supported by use of metacognitive strategies (especially concept mapping), opportunities to research the development of their peers' NOS understanding and the chance to discuss case studies of elementary science classes oriented towards NOS teaching. A further raft of studies point to the key role played by teachers' NOS-oriented pedagogical content knowledge, curriculum awareness, confidence, self-efficacy and access to appropriate curriculum resources (Hanuscin et al. 2011; Lederman et al. 2012; Ryder and Leach 2008). My own views on how we can build and implement a curriculum to achieve enhanced levels of NOS understanding are discussed at length in Hodson (2009).

It is both notable and disappointing that the gains in NOS understanding consequent on exposure to explicit, reflective instruction are considerably less substantial in relation to the sociocultural dimensions of science than for other NOS elements.[23] The drive to equip students with an understanding of science in its social, cultural, economic and political contexts is, of course, the underpinning rationale of the so-called science-technology-society (STS) approach – more recently expanded to STSE (where E stands for environment). STS(E) has always been a purposefully ill-defined field that leaves ample scope for varying interpretations and approaches, and much has changed over the years in terms of its priorities and relative emphases.[24]

Aikenhead (2005, 2006) describes how the early emphasis on values and social responsibility was systematized by utilizing a theoretical framework deriving from sociology of science and encompassing two key aspects of NOS: (i) the social interactions of scientists *within* the scientific community and (ii) the interactions of science and scientists with social aspects, issues and institutions *external* to the community of scientists. In the terms used by Helen Longino (1990), this is a distinction between the *constitutive* values of science (the drive to meet criteria of truth, accuracy, precision, simplicity, predictive capability, breadth of scope and problem-solving capability) and the *contextual* values that impregnate the personal, social and cultural context in which science is organized, supported, financed and conducted. Allchin (1999) draws a similar distinction between the *epistemic* values of science and the *cultural* values that infuse scientific practice. Both emphases

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[23] Akerson et al. (2000), Dass (2005), Lederman et al. (2001), Moss et al. (2001), Tairab (2001), and Zémplen (2009).

[24] Aikenhead (2003, 2005), Barrett and Pedretti (2006), Bennett et al. (2007), Cheek (1992), Fensham (1988), Gallagher (1971), Gaskell (2001), Hurd (1997), Kumar and Chubin (2000), Lee (2010), Nashon et al. (2008), Pedretti (2003), Pedretti and Nazir (2011), Solomon and Aikenhead (1994), and Yager (1996).

have remained strong, though much has changed with respect to the sociopolitical and economic contexts in which educators and scientists work, our understanding of key issues in the history, philosophy and sociology of science and our theoretical knowledge concerning concept acquisition and development.

Drawing on the metaphor deployed by Sauvé (2005) in her analysis of trends in environmental education, Pedretti and Nazir (2011) describe variations and shifts in the focus of STSE in terms of 'a vast ocean of ideas, principles, and practices that overlap and intermingle one into the other' (p. 603). The six currents identified are as follows: *application/design* (practical problem solving through designing new technology or adapting old technologies), *historical* (understanding the sociocultural embeddedness of science and technology), *logical reasoning* (using a range of perspectives, including many outside science, to understand scientific and technological developments), *value-centred* (addressing the multidimensionality of socioscientific issues, including moral-ethical concerns), *sociocultural* (recognizing and critiquing science and technology as social institutions) and *socio-ecojustice* (critiquing and addressing socioscientific issues through direct and indirect action). Five of these categories include elements of NOS, as defined above.

Concern with constitutive and contextual values, and the ways in which these values have shifted in recent years, has been the trigger for renewed interest in the changing nature of NOS – in particular, the key differences between contemporary practice at the cutting edge of scientific research and what might be called 'classical scientific research' (the focus for much of school science), especially with regard to methods, publication practices, sponsorship and funding. Forty years ago, sociologist Robert Merton (1973) identified four 'functional norms' or 'institutional imperatives' that govern the practice of science and the behaviour of individual scientists, whether or not they are aware of it. These norms are not explicitly taught; rather, newcomers are socialized into the conventions of scientific practice through the example set by more senior scientists. Merton argued that these norms constitute the most effective and efficient way of generating new scientific knowledge and provide a set of 'moral imperatives' that serves to ensure good and proper conduct:

- *Universalism* – science is universal (i.e. its validity is independent of the context in which it is generated or the context in which it is used) because evaluation of knowledge claims in science uses objective, rational and impersonal criteria rather than criteria based on personal, commercial or political interests and is independent of the reputation of the particular scientist or scientists involved.
- *Communality* – science is a cooperative endeavour and the knowledge it generates is publicly owned. Scientists are required to act in the common good, avoid secrecy and publish details of their investigations, methods, findings and conclusions so that all scientists may use and build upon the work of others.
- *Disinterestedness* – science is a search for truth simply for its own sake, free from political or economic motivation or strictures, and with no vested interest in the outcome.
- *Organized scepticism* – all scientific knowledge, together with the methods by which it is produced, is subject to rigorous scrutiny by the community of scientists in conformity with clearly established procedures and criteria.

In the traditional forms of basic or fundamental research, usually located in universities and/or government research institutes, the so-called pure scientists constitute their own audience: they determine the research goals, recognize competence, reward originality and achievement, legitimate their own conduct and discourage attempts at outside interference. In the contemporary world, universities are under increasing public pressure to deliver more obvious value for money and to undertake research that is likely to have practical utility or direct commercial value. There are increasingly loud calls for closer links between academia and industry. In this changed sociopolitical environment, scientists are now required to practice what Ziman (2000) calls *post-academic* science.[25] Because contemporary scientific research is often dependent on expensive technology and complex and wide-ranging infrastructure, it must meet the needs and serve the interests of those sponsors whose funds provide the resources. Research is often multidisciplinary and involves large groups of scientists, sometimes extending across a number of different institutions, working on problems that they have not posed, either individually or as a group. Within these teams, individual scientists may have little or no understanding of the overall thrust of the research, no knowledge of their collaborators at a personal level and no ownership of the scientific knowledge that results. A number of governments and universities have moved to privatize their research establishments, that is, sell institutes or laboratories engaged in potentially commercially lucrative research areas to industry and business interests or turn them into independent companies. In consequence, scientists have lost a substantial measure of autonomy. In many universities, the research agenda no longer includes so-called blue skies research (i.e. fundamental research), as emphasis shifts to *market-oriented research*, *outcome-driven research* and ever-shortening *delivery times*. Many scientists are employed on contracts that prevent them from disclosing all their results. Indeed, there is a marked trend towards patenting, privatization and commodification of knowledge. As Ziman (2000) comments, many scientists have been forced to trade the academic kudos of publication in refereed journals for the material benefit of a job or a share in whatever profit there might be from a patented invention.

Varma's (2000) study of the work of scientists in industry paints a vivid picture of disturbing changes in the way research is conducted: customization of research to achieve marketable outcomes, contract funding and strict budget constraints, flexible but strictly temporary teams of researchers assembled for specific projects and a shift in the criteria for research appraisal from the quality and significance of the science to cost-effectiveness. The vested interests of the military and commercial sponsors of research, particularly tobacco companies, the petroleum industry, the food processing industry, agribusiness institutions and pharmaceutical companies, can often be detected not just in research priorities but also in research design, especially in terms of what and how data are collected, manipulated and presented. More subtly, in what data are *not* collected, what findings are omitted from reports and whose

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[25] While Ziman (2000) refers to contemporary scientific practice as *post-academic science*, Funtowicz and Ravetz (1993) call it *post-normal science,* and Gibbons and colleagues (1994) and Nowotny et al. (2003) use the term *mode 2 science*.

voices are silenced. Commercial interests may influence the way research findings are made public (e.g. press conferences rather than publication in academic journals) and the way in which the impact of adverse data is minimized, marginalized, hidden or ignored – issues explored at length in Hodson (2011).

In summary, science can no longer be regarded as the disinterested search for truth and the free and open exchange of information, as portrayed in many school textbook versions of science. Rather, it is a highly competitive enterprise in which scientists may be driven by self-interest and career building, desire for public recognition, financial inducements provided by business and commerce or the political imperatives of military interests. Some would argue that one of the most disturbing features of contemporary science is the effective privatization of knowledge. Science is increasingly conducted behind closed doors, in the sense that many procedures and findings remain secret or they are protected by patenting, thus removing them from critical scrutiny by the community of scientists. The scope of what can be patented has been progressively and systematically broadened, such that the very notion of public accessibility to the store of contemporary scientific knowledge is under threat (Mirowski and Sent 2008). It seems that the realities of contemporary science are in direct contradiction of three, if not all four, of the functional norms identified by Merton. Communality, disinterestedness and organized scepticism have been replaced by ‘the entrepreneurial spirit and economic growth, such that scientific intellectual creativity seems to have become synonymous with commodity’ (Carter 2008, p. 626). Our definitions of NOS and the teaching/learning activities we provide in school need to take account of these matters.

28.11 SSI-Oriented Teaching and Its Curriculum Implications

Interestingly, as consideration of the nature of science has become a much more prominent part of regular science curricula, even a central part in many educational jurisdictions, so emphasis in STSE education has shifted much more towards confrontation of socioscientific issues (SSI), what Pedretti and Nazir (2011) call the value-centred current in STSE. Zeidler and colleagues (2005) contrast this orientation with earlier forms of STS or STSE education in terms of its emphasis on developing habits of mind (specifically, developing scepticism, maintaining open-mindedness, acquiring the capacity for critical thinking, recognizing that there are multiple forms of inquiry, accepting ambiguity and searching for data-driven knowledge) and ‘empowering students to consider how science-based issues reflect, in part, moral principles and elements of virtue that encompass their own lives, as well as the physical and social world around them’ (p. 357). They argue that while STSE education emphasizes the impact of scientific and technological development on society, it does not focus explicitly on the moral-ethical issues embedded in decision-making: ‘STS(E) education as currently practiced… only ‘points out’ ethical dilemmas or controversies, but does not necessarily exploit the inherent pedagogical power of discourse, reasoned argumentation, explicit NOS considerations, emotive, developmental, cultural or epistemological connections within the issues themselves… nor does it consider the moral or character development of students' (p. 359).

Bingle and Gaskell (1994) had earlier noted that STS education tends to emphasize what Bruno Latour (1987) calls 'ready-made science' (with all its attendant implicit messages about certainty) rather than 'science in the making' (with its emphasis on social construction). Simmons and Zeidler (2003) argue that it is the priority given to science in the making through consideration of *controversial* SSI that gives the SSI approach its special character and its unique power to focus on NOS understanding: 'Using controversial socioscientific issues as a foundation for individual consideration and group interaction provides an environment where students can and *will* develop their critical thinking and moral reasoning' (p. 83, emphasis added). In a further attempt at delineation, Zeidler and colleagues (2002) claim that the SSI approach has much broader scope, in that it 'subsumes all that STS has to offer, while also considering the ethical dimensions of science, the moral reasoning of the child, and the emotional development of the student' (p. 344).[26] Robust understanding of NOS is a clear prerequisite for addressing SSI critically and systematically; importantly, enhanced NOS understanding (both *distal* and *proximal*) is also a significant learning outcome of an SSI-oriented approach (Schalk 2012).

If students are to address SSI thoroughly and critically and deal with the NOS issues they raise, they will need the language skills to access knowledge from various sources and the ability to express their knowledge, views, opinions and values in a form appropriate to the audience being addressed. Thus, teachers need to focus students' attention very firmly on the language of science, scientific communication and scientific argumentation and on students' capacity to become critical readers of a wide variety of texts. Because meaning in science is also conveyed through symbols, graphs, diagrams, tables, charts, chemical formulae and equations, 3-D models, mathematical expressions, photographs, computer-generated images, body scans and so on, Lemke (1998) refers to the language of science as 'multimodal communication'. Any one scientific text might contain an array of such modes of communication, such that it may be more appropriate to refer to the *languages* of science:

> Science does not speak of the world in the language of words alone, and in many cases it simply cannot do so. The natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual mathematical expression. (Lemke 1998, p. 3)

Because much of the information needed to address SSI is of the science-in-the-making kind, rather than a well-established science, and may even be located at or near the cutting edge of research, it is unlikely that students will be able to locate it

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[26] See also Eastwood and colleagues (2012), Ekborg and colleagues (2012), Khishfe (2012b), Lee (2012), Lee and Grace (2012), Nielsen (2012b), Robottom (2012), Sadler (2009, 2011), Sadler and Donnelly (2006), Sadler and Zeidler (2005a, b), Sadler and colleagues (2004, 2006, 2007), Schalk (2012), Tytler (2012), Wu and Tsai (2007), Zeidler and Sadler (2008a, b), Zeidler and Schafer (1984), and Zeidler and colleagues (2003, 2005, 2009).

in traditional sources of information like textbooks and reference books. It will need to be accessed from academic journals, magazines, newspapers, TV and radio broadcasts, publications of special interest groups and the Internet, thus raising important issues of *media literacy*. Being media literate means being able to access, comprehend, analyse, evaluate, compare and contrast information from a variety of sources and utilize that information judiciously and appropriately to synthesize one's own detailed summary of the topic or issue under consideration. It means recognizing that the deployment of particular language, symbols, images and sound in a multimedia presentation can each play a part in determining a message's overall impact and will have a profound influence on its perceived value and credibility. It means being able to ascertain the writer's purpose and intent, determine any subtext and implicit meaning and detect bias and vested interest. It means being able to distinguish between good, reliable information and poor, unreliable information. It involves the ability to recognize what Burbules and Callister (2000) call *misinformation*, *malinformation*, *messed-up information* and *useless information*. Students who are media literate understand that those skilled in producing printed, graphic and spoken media use particular vocabulary, grammar, syntax, metaphor and referencing to capture our attention, trigger our emotions, persuade us of a point of view and, on occasions, bypass our critical faculties altogether.

Many SSI are highly controversial, sometimes because the scientific information required to formulate a judgement is incomplete, insufficient, inconclusive or extremely complex and difficult to interpret, sometimes because judgement involves consideration of factors rooted in social, political, economic, cultural, religious, environmental, aesthetic and/or moral-ethical concerns, beliefs, values and feelings. In other words, controversy may be *internal* or *external* to science. Teachers need to make a decision about how they will handle such issues. Should they try to avoid controversy altogether, take a neutral position, adopt the devil's advocate role, try to present a balanced view or advocate a particular position? These questions are discussed at length in Hodson (2011). Further, almost any discussion of a topical SSI is likely to raise questions not only about what we *can* or *could* do but also about what is the *right* decision and what we *ought* to do. Because many SSI have this moral-ethical dimension, teachers will also need to foster students' moral development and develop their capacity to make ethical judgments. Helpful discussion of these matters and strategies that teachers might employ can be found in Fullick and Ratcliffe (1996), Jones et al. (2007, 2010) and Reiss (1999, 2003, 2010).[27]

It is also likely that addressing SSI in class will generate strong feelings and emotions, with students' views and assumptions being strongly influenced by personal experiences and the experiences of friends and family and by socioculturally determined predispositions and worldviews. A student's sense of identity, comprising

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[27] See also Beauchamp and Childress (2008), Clarkeburn (2002), Goldfarb and Pritchard (2000), Keefer (2003), Levinson and Reiss (2003), Sadler and Zeidler (2004), Sáez et al. (2008), and Saunders and Rennie (2013).

ethnicity, gender, social class, family and community relationships, economic status and personal experiences extending over many years, will necessarily impact on their values, priorities and preferences and influence the ways in which they engage in discussion and the conclusions they reach. Teachers introducing SSI into the curriculum need to be sensitive to these influences and will need to assist students in dealing with potentially stressful and disconcerting learning situations. It is here that notions of *emotional intelligence*, *emotional literacy* and *emotional competence* can be helpful.[28] Although these three terms are closely related, Matthews (2005) chooses to draw a distinction between the individualistic nature of emotional intelligence and the strongly social nature of emotional literacy. Thus, he argues emotional intelligence refers to an individual's ability to perceive, describe, appraise and express emotions, understand emotions and emotional knowledge, access and/or generate appropriate feelings when they facilitate thought or manage them productively when they might inhibit, while emotional literacy is the capacity to be receptive to a wide range of feelings, empathize with others and continuously monitor the emotional climate in which one is located. Emotional competence may be seen as an amalgam of the two. In general, the goal of emotional literacy is awareness and management of one's emotions in both joyful and stressful situations, the confidence and self-assurance to understand one's own emotions and the capacity to deal with them in a positive and intentional way. It is closely related to notions of self-awareness, self-image, self-esteem and sense of identity, and less directly with self-efficacy and agency.

28.12 Future Developments

In a chapter dealing with the origin, development, implications and shifting emphases of NOS-oriented curricula, it is perhaps appropriate to speculate on future developments or even to promote one's own ideas for further development. On this latter count, I count myself among those authors who argue that current conceptions of STSE or SSI-oriented science education do not go far enough, among those who advocate a much more radical, politicized form of SSI-oriented teaching and learning in which students not only address complex and often controversial SSI, and formulate their own position concerning them, but also prepare for, and engage in, sociopolitical actions that they believe will 'make a difference', asking critical questions about how research priorities in science are determined, who has access to science, how science could (and perhaps should) be conducted differently, how scientific and technological knowledge are deployed, whose voices are heard and whose reading

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[28] Goleman (1985, 1996, 1998), Matthews et al. (2002), Matthews and colleagues (2004a, b), Saarni (1990, 1999), Salovey and Meyer (1990), Salovey and Shayter (1997), Steiner (1997), Sharp (2001) and Zeidner et al. (2009).

of a situation are considered.[29] It is a curriculum clearly rooted in notions of equity and social justice.

The likelihood of students becoming active citizens in later life is increased substantially by encouraging them to take action *now* (in school), providing opportunities for them to do so and giving examples of successful actions and interventions engaged in by others. Students need knowledge of actions that are likely to have positive impact and knowledge of how to engage in them. A key part of preparing for action involves identifying action possibilities, assessing their feasibility and appropriateness, ascertaining constraints and barriers, resolving any disagreements among those who will be involved, looking closely at the actions taken by others (and the extent to which they have been successful) and establishing priorities in terms of what actions are most urgently needed (and can be undertaken fairly quickly) and what actions are needed in the longer term. It is essential, too, that all actions taken by students are critically evaluated and committed to an action database for use by others. From a teaching perspective, it is important that care is taken to ensure both the appropriateness of a set of actions for the particular students involved and the communities in which the actions will be situated and the overall practicality of the project in terms of time and resources. It is also essential that students gain robust knowledge of the social, legal and political system(s) that prevails in the communities in which they live and develop a clear understanding of how decisions are made within local, regional and national government and within industry, commerce and the military. Without knowledge of where and with whom power of decision-making is located and awareness of the mechanisms by which decisions are reached, effective intervention is not possible. Thus, an issue-based and action-oriented curriculum requires a concurrent programme designed to achieve a measure of *political literacy*, including knowledge of how to engage in collective action with individuals who have different competencies, backgrounds and attitudes, but shares a common interest in a particular SSI. It also includes knowledge of likely sympathizers and potential allies and strategies for encouraging cooperative action and group interventions.

Desirable as this approach may be in meeting the needs of citizens in the early twenty-first century, converting such curriculum rhetoric into practical action in real classrooms is an extraordinarily tall order for teachers to undertake. It is a tall order for three reasons. First, because it radically changes the nature of the school curriculum and puts a whole raft of new demands on teachers. Second, because it challenges many of the assumptions on which schooling is traditionally based. Third, because it is predicated on a commitment to bringing about extensive and wide-ranging social change at local, regional, national and international levels. It will only occur when sufficient teachers, teacher educators, curriculum developers and curriculum policy makers are convinced of the importance, desirability and feasibility of

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[29] See also Alsop (2009), Alsop and colleagues (2009), Bencze and Alsop (2009), Bencze and colleagues (2009b, 2012), Bencze and Sperling (2012), Calabrese Barton and Tan (2009, 2010), Chawla (2002a, b), Hart (2008b, c), Hodson (2003, 2011, 2014), Mueller (2009), Mueller et al. (2013), Roth (2009a, b, 2010), Roth and Désautels (2002, 2004), and Santos (2008).

addressing SSI in the science classroom and encouraging sociopolitical action, and when there is commitment to teach and confidence in doing so through awareness of appropriate pedagogical strategies, capacity to organize the required classroom environment and access to suitable resources. The real breakthrough will come when individual teachers are able to find and work with like-minded colleagues to form pressure groups that can begin to influence key decision-making bodies. However, such matters are well outside the scope of this chapter.

28.13 Final Thoughts

The primary purpose of this chapter has been to convey something of the extraordinary rise and widening scope of curriculum interest in NOS understanding. From very humble beginnings (e.g. 'Let's ensure that we teach about the methods that scientists use as well as paying attention to content'), curriculum interest in NOS has developed into a major influence on science education in many parts of the world. Changing views of what counts as NOS knowledge have led to further extensive developments, including concern with the characteristics of scientific inquiry, the role and status of the scientific knowledge it generates, modelling and the nature of models, how scientists work as a social group, the linguistic conventions for reporting and scrutinizing knowledge claims, the ways in which science impacts and is impacted by the social context in which it is located and the centrality of NOS in addressing the science underpinning SSI. More recently, it has been extended in such a way that some educators see NOS as a central plank in citizenship education. In my view, the next development in the extension of NOS-oriented education is the establishment of an issue-based and action-oriented curriculum capable of directing critical attention to (i) the way contemporary research and development in science and technology is conceived, practised and funded and (ii) the ways in which scientific knowledge is accessed and deployed in establishing policy and priorities with respect to SSI.

A key issue concerns the NOS sophistication we should pursue via the school curriculum. It is unrealistic as well as inappropriate to expect students to become highly skilled philosophers, historians and sociologists of science. Rather, we should select NOS items for the curriculum in relation to important educational goals: the need to motivate students and assist them in developing positive but critical attitudes towards science, the need to pay close attention to the cognitive goals and emotional demand of specific learning contexts, the creation of opportunities for students to experience *doing* science for themselves, the capacity to address complex socioscientific issues with critical understanding, concern for values issues and so on. The degree of sophistication of the NOS items we include should be appropriate to the stage of cognitive and emotional development of the students and compatible with other long- and short-term educational goals. There are numerous goals for science education (and education in general) that can, will and *should* impact on decisions about the NOS content of lessons. Our concern is not just good philosophy of science, good sociology of science or good history of science, not just authenticity and preparation for sociopolitical action, but the educational needs and interests of the students – *all* students. Selection of NOS items should consider the *changing* needs and interests of students at different stages of their science education, as well as take cognizance of the views of 'experts' (philosophers of science, historians of science, sociologists of science, scientists, science educators) and the need to promote the wider goals of (i) authentic representation of science and (ii) pursuit of critical scientific literacy.

It is considerations like these that prompted Michael Matthews (1998) to advocate the pursuit of 'modest goals' concerning HPS in the school science curriculum. In his words, 'there is no need to overwhelm students with cutting edge questions' (p. 169). Perhaps so, but agreement with the notion of modest goals still raises a question of what they should comprise. At the very least, we should include the following: consideration of the relationship between observation and theory; the role and status of scientific explanations (including the processes of theory building and modelling); the nature of scientific inquiry (including experiments, correlational studies, blind and double-blind trials, data mining and all the other notable variations among the subdisciplines of science); the history and development of major ideas in science; the sociocultural embeddedness of science and the interactions among science, technology, society and environment; the distinctive language of science; the ways in which scientific knowledge is validated through criticism, argument and peer review; moral-ethical issues surrounding science and technology; error, bias, vested interest, fraud and the misuse of science for sociopolitical ends; and the relationship between Western science and indigenous knowledge. A number of these elements are present in some science curricula, but more often than not, they are implicit, part of the hidden curriculum, embedded in language, textbook examples, laboratory activities and the like, and so dependent, ultimately, on teachers' nature of science views.

This is a demanding prescription and I readily acknowledge that telling students too early in their science education that scientific inquiry is context dependent and idiosyncratic could be puzzling, frustrating and even off-putting. This is a similar point to Brush's (1974) concern that teaching history of science can have an adverse effect on young students by undermining their confidence in science and scientists. One approach is to take our cue from secondary school chemistry curricula, where we often begin with some very simple representations, such as 'elements are either metals or non-metals' or 'bonding is either covalent or electrovalent'. We then proceed to qualify these assertions in all manner of ways: 'there are varying degrees of metallic/non-metallic character, depending on atomic size and electron configuration' and 'there is a range of intermediate bond types, including polarized covalent bonds and lattices involving highly distorted ions, as well as hydrogen bonding, van der Waal's forces, and so on'. Similarly, in the early years, we may find it useful to characterize scientific inquiry as a fairly standard set of steps. Within this simple representation, we can emphasize the importance of making careful observations (using whatever conceptual frameworks are available and appropriate to the students' current stage of understanding), taking accurate measurements, systematically controlling variables, and so on. As students become more experienced, they can be introduced to variations in approach that are necessary as contexts change – for example, the startlingly different approaches adopted by experimental particle physicists, synthetic organic chemists and evolutionary biologists.

Matthews (2012) makes the same point when he states that students have 'to crawl before they can walk, and walk before they can run. This is no more than commonsensical pedagogical practice' (p. 21). The shift from nature of science (NOS) to features of science (FOS), with its inbuilt recognition of diversity among the sciences and the significant changes in constitutive values from 'classical' scientific research to contemporary, post-Mertonian scientific practice, would be a major step in assisting teachers to pitch their teaching at a level appropriate to the students and to the issues being addressed.

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Chapter 29
The Development, Use, and Interpretation of Nature of Science Assessments

Norman G. Lederman, Stephen A. Bartos, and Judith S. Lederman

29.1 Introduction

In the end, assessment becomes critical when considering the various goals of science curricula and instruction. This is as true for nature of scientific knowledge (NOS), typically considered synonymous with nature of science, as it is for any science subject matter. Hence, it is critical to delineate both the rationale for teaching the construct and its meaning.

The construct "nature of scientific knowledge" has been and continues to be an advocated goal of science education, as reflected in numerous US reform documents (e.g., American Association for the Advancement of Science [AAAS] 1990, 1993; National Research Council [NRC] 1996; National Science Teachers Association [NSTA] 1982) as well as other reform documents globally. Although conceptions of NOS, as reflected in these documents, have changed as much as the scientific knowledge they characterize, in general, an understanding of NOS is defended as being a critical component of scientific literacy. In spite of the arguments presented by a handful of researchers (e.g., Allchin 2011, 2012; Wong and Hodson 2009, 2010) contending that the views of NOS presented in these documents, and undergirding much of current NOS research, are not representative of the real work of scientists, it is important to note that the aspects of NOS outlined in the sections that follow are derived from careful examination of the writings of scientists, historians of science, and philosophers of science. Regardless, it is important not to lose sight of the audience for the often cited aspects of NOS, K-12 students. Consequently,

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when one begins to consider what aspects of NOS should be included in school curricula, developmental appropriateness and relevance/importance to daily life must be addressed. Most importantly, there does exist a relatively clear consensus supporting a group of scientifically, developmentally, and educationally appropriate (K-12) aspects of NOS. But, before unpacking the construct, it would seem appropriate to first explicate what is meant by "scientific literacy."

The view of scientific literacy used here is informed by Roberts' (2007) two "visions" of literacy that have been exemplars within the science education community. The first, "science literacy," is related to an understanding of the traditional science content, namely, the specific knowledge, processes, and products of a discipline, as it focuses "inward at the canon of orthodox natural science" (Roberts 2007, p. 2). "Scientific literacy" includes the ability to apply this conceptual knowledge and understanding of the processes of science to help inform personal decision-making and participation in a scientifically and technology-driven culture and economy (AAAS 1993; NRC 1996). While formalized by Showalter (1974) and the National Science Teachers Association (1982), the various arguments regarding the importance of NOS in the development of scientific literacy can best be understood by examining Driver et al. (1996). Specifically, Driver and colleagues contended that understanding NOS is necessary (1) in helping individuals comprehend "everyday" science and the related technology and process of their lives (utilitarian), (2) to aid in making informed decision-making when confronted with socio-scientific issues (democratic), (3) in fostering an appreciation of the value that science adds to contemporary culture (cultural), (4) in helping cultivate an understanding of moral commitments of the scientific community and their value to society as a whole, and (5) in facilitating the learning of science subject matter.

While scientific literacy has arguably become a principal and overarching goal of science education worldwide (Roberts 2007), unfortunately, and in spite of the preponderance of NOS as an objective of science education for over 100 years (Central Association of Science and Mathematics Teachers 1907; Kimball 1967–68; Lederman 1992), it is largely intuition that underpins these five arguments in favor of developing learners' understandings of NOS. Little empirical support can be found in the science education literature to support the various rationales for developing understandings of NOS. This is due, in no small part, to the challenges of improving individual's conceptions of NOS, as "the longevity of this educational objective has been surpassed only by the longevity of students' inability to articulate the meaning of the phrase 'nature of science,' and to delineate the associated characteristics of science" (Lederman and Niess 1997, p. 1). The obstacles involved in seeing teachers' informed views of NOS translated into their classroom practice further complicate this process. Moreover, without a sufficient number of NOS-informed individuals, there is no way to know if or how NOS contributes to the development of a scientifically literate populace. Unfortunately, existing data concerning understandings of NOS still support Shamos (1984) who, when speaking to the necessity of developing students' understandings of what we now refer to as NOS, concluded that "in spite of taking science classes, few students come through this experience with more than a fleeting glimpse of science, and fewer still retain any lasting impression of the scientific world" (p. 333).

29.2 What Is Nature of Scientific Knowledge?

Fortunately, in spite of the dearth of research specifically relating NOS to the development of scientific literacy, there is over 60 years of research on NOS that has, in part, sought to assess teachers' and students' understandings of NOS and investigate the efficacy of various approaches to improving these conceptions (Lederman 2007). But, irrespective of this ever growing body of research, the continued support for NOS in the science education and scientific communities and explicit statements regarding NOS in various reform documents, there are still unproductive disagreements regarding the meaning of NOS. Prior to delineating the specific conception of NOS espoused here, a few issues must be clarified.

First, the myriad views of NOS reflected on the pages of refereed journals and conference proceedings, which almost invariably contradict the aforementioned reform documents, do not provide direct support for the contention that there is, therefore, no consensus about the meaning of NOS as some have contended (e.g., Alters 1997). Not only is there more consensus than disagreement about the definition and/or meaning of NOS (Smith et al. 1997; Smith and Scharmann 1999), these disagreements, while providing fodder for a lively argument among philosophers, historians, or science educators, are irrelevant to K-12 classroom practice (Lederman 1998, 2007). What is necessary when considering NOS, as is the case with typical science content, is its educational and developmental appropriateness, as well as its presentation in a way that is connected with students' lives, but at an acceptable level of generality, as reflected in the aforementioned authors as well as others (e.g., Elby and Hammer 2001; Rudolph 2003). Little disagreement exists among philosophers, historians, and science educators for the characteristics of NOS that fit these criteria.

Second, it is important to stress that a definitive description of NOS, contrary to the assumptions of our critics (Irzik and Nola 2011; Matthews 2012), is not presented here or elsewhere. It is recognized, and it should be obvious, that other researchers may include or delete various aspects of NOS resulting in equally valid representations of NOS that are educationally and developmentally appropriate for learners (Osborne et al. 2003; Smith and Scharmann 1999). Far too much time has recently been spent arguing about what aspects of NOS should and should not be included in various lists of desired outcomes and standards. The discussion should be more centered on the value of the knowledge that is being considered, not the construction of a definitive definition of NOS. The focus here is not to simply promote the definition of the construct provided by favored colleagues and fellow researchers[1] but to assist the reader in delineating NOS from both the process of science and the scientific knowledge that results. The conflation of the processes of science (scientific inquiry), with the characteristics of scientific knowledge that are inherently derived from these processes (nature of science scientific knowledge, NOS), is an avoidable, yet common, characteristic of research done on NOS.

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[1] See, for instance, Abd-El-Khalick (2005), Akerson et al. (2000), Bell and Lederman (2003), Khishfe and Abd-El-Khalick (2002), Lederman and Neiss (1997), and Schwartz and Lederman (2002).

Lastly, it should be reiterated that a focus on learning outcomes that are developmentally appropriate have a preponderance of empirical support for inclusion in K-12 curricula and are arguably essential if students are to achieve the goal of scientific literacy should be in the forefront of discussions about NOS. Furthermore, at this level of appropriate generality, there are few disagreements about aspects of NOS, as evidenced by their congruence with numerous reform documents worldwide. Consider the issue of the existence of an objective reality versus that which is purely phenomenal. This debate may certainly be situated in a philosophy of science class but is misplaced, misaligned, and counterproductive to the goals and objectives of K-12 science curricula. The reader is reminded that the goal of the K-12 science teacher is not to create philosophers of science, but rather to develop informed citizens so decisions can be made concerning personal and societal issues that are scientifically based. This goal is sometimes overlooked by participants in NOS disputes.

29.3 The Nature of Scientific Knowledge (NOS)

In general, the phrase "nature of scientific knowledge" or NOS refers to the characteristics of scientific knowledge that are inherently derived from the manner in which it is produced (i.e., scientific inquiry). These general characterizations aside, philosophers and historians of science, scientists, and science educators do not, nor should they be expected to, share a common consensus on a specific definition of NOS. This, as previously mentioned, should not be cause for alarm, as over the last century conceptions of NOS have changed just as conceptions of science have done, with the definition of NOS changing as much as the knowledge it intends to characterize.[2]

It is of utmost importance that the 1980s saw the phrase "nature of scientific knowledge" shortened to "nature of science," a modification that may have introduced some unnecessary confusion. In the research literature, "nature of science" more aptly refers to "nature of scientific knowledge" and is consistent with the definition used in the current chapter. Lastly, to reiterate, the "list" of characteristics of scientific knowledge that will be explicated in what follows is educationally and developmentally appropriate and has a wealth of evidence in support of their inclusion in K-12 science instruction – they should not be construed as representing the definitive "NOS catechism," as some have decreed (Matthews 2012). Furthermore, while some researchers have maintained that these aspects of NOS do not present the "whole picture" of science as it is practiced by scientists (e.g., Allchin 2011, 2012; Wong and Hodson 2009, 2010), these aspects are, the reader is reminded, derived

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[2] As evidenced by AAAS (1990, 1993), Center of Unified Science Education (1974), Central Association for Science and Mathematics Teachers (1907), Klopfer and Watson (1957), and NSTA (1982).

from the writings and recommendations of scientists and are not intended to help inform efforts to create a new population of bench scientists, but to aid K-12 classroom science teachers and science education researchers in the development of a scientifically literate populace. With these caveats, let us return to unpacking the construct of NOS.

First, learners should develop an understanding of the crucial distinction between observation and inference. In the K-12 science classroom, observations are presented as descriptive statements about natural phenomena that are "directly" accessible to the senses, or extensions of the senses, and for which observers can reach consensus with relative ease (e.g., an object, once released, falls to the floor). Inferences, by contrast, are statements that are not "directly" accessible to the senses and can only accessed and/or measured though related manifestations or effects (e.g., gravity). Beyond developing explanations, at a higher level, scientists can infer models and/or mechanisms that serve to explain observations of complex phenomena (e.g., weather modeling, evolution).

Second is the distinction between scientific theories and laws, a pair of categories of scientific knowledge that is closely related to the distinction between observation and inference. This point is critical as the majority of individuals hold a simplistic, hierarchical view of the relationship between theories and laws, whereby theories, once they have "accumulated" sufficient supportive evidence, become laws. It follows from this misconception that scientific laws have a higher status than scientific theories, when in fact scientific theories and laws are different types of knowledge. A theory is not formulated with the hope that someday it will acquire the status of "law," as theories are not developed or transformed into laws, nor is a law ever demoted to being "just a theory." Scientific laws are statements or descriptions of the relationships among observable phenomena. Boyle's law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Scientific theories, by contrast (and in contrast to the common usage of the word "theory"), are inferred explanations for observable phenomena. The kinetic molecular theory, which explains Boyle's law, is one example. Moreover, theories are as legitimate a product of science as laws. Scientific theories, in their own right, serve important roles, such as guiding investigations and generating new research problems, in addition to explaining relatively huge sets of seemingly unrelated observations in more than one field of investigation. For example, the kinetic molecular theory serves to explain phenomena that relate to changes in the physical states of matter, others that relate to the rates of chemical reactions, and still other phenomena that relate to heat and its transfer, to mention just a few. While some philosophers and historians of science (e.g., Allchin 2012; Wong and Hodson 2009, 2010) may contend that these descriptions of laws and theories leave something to be desired, this level of generality has evidenced itself as appropriate and accessible to K-12 science students. Indeed, these same critics of including the distinction of theories and laws under the rubric of NOS base their positions on the idea that scientists do not enter discussions about such differences in knowledge claims. In spite of this, the audience of such NOS instruction cannot be ignored. The commonly held misconception that "evolution is just a theory" is case in point. Although the distinction between theories and laws may not be important to scientists, it is certainly important for the general public, teachers, and students.

Third, the development of scientific knowledge involves human imagination and creativity. Science, contrary to common belief, does not rely solely on observations of the natural world (i.e., empirically based), nor is it totally lifeless, rational, and orderly. In addition to devising creative investigatory methodologies and data reduction techniques, science involves the invention of explanations and the generation of ideas that involve considerable creativity by scientists. The “leap” from atomic spectral lines to Bohr’s model of the atom with its elaborate orbits and energy levels is one example. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality.

Fourth, scientific knowledge, owing to scientists’ theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations, is unavoidably subjective. These background factors form a mind-set that affects the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), what they consider as evidence, and how they make sense of and interpret their observations. It is this (sometimes collective) individuality or mind-set that accounts for the role of subjectivity in the production of scientific knowledge. It is noteworthy that, contrary to common belief, science rarely starts with neutral observations (Chalmers 1982). Observations (and investigations) are motivated by, guided by, and acquire meaning in reference to questions or problems, which, in turn, are derived from within certain theoretical perspectives. Often, hypothesis or model testing serves as a guide to scientific investigations. For example, a researcher operating from a Darwinian framework might focus his/her efforts on the location of transitional species. By contrast, from a punctuated equilibrist perspective, transitional species would not be expected, nor would what a Darwinian considered a transitional species be considered as such (see Gould and Eldridge 1977).

Fifth, science as a human enterprise is practiced in the context of a larger culture, and its practitioners (scientists) are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion. Telling the story of the evolution of humans (*Homo sapiens*) over the course of the past seven million years is central to the biosocial sciences and serves to illustrate how social and cultural factors impact scientific knowledge. Scientists have formulated several elaborate and differing story lines about this evolution. Until recently, the dominant story was centered about “the man-hunter” and *his* crucial role in the evolution of humans to the form we now know (Lovejoy 1981). This scenario was consistent with the white-male culture that dominated scientific circles up to the 1960s and early 1970s. As the feminist movement grew stronger and women were able to claim recognition in the various scientific disciplines, the story about hominid evolution started to change. One story that is more consistent with a feminist approach is centered about “the female-gatherer” and *her* central role in the evolution of humans (Hrdy 1986). It is noteworthy that both story lines are consistent with the available evidence.

Sixth, it follows from the previous discussions that scientific knowledge is never absolute or certain. This knowledge, including "facts," theories, and laws, while durable, is tentative and subject to change. Scientific claims change as new evidence, made possible through advances in *theory* and technology, is brought to bear on existing theories or laws or as old evidence is reinterpreted in the light of new theoretical advances or shifts in the directions of established research programs. It should be emphasized that tentativeness in science does not only arise from the fact that scientific knowledge is inferential, creative, and socially and culturally embedded. There are also compelling logical arguments that lend credence to the notion of tentativeness in science. Indeed, contrary to common belief, scientific hypotheses, theories, and laws can *never* be absolutely "proven." This holds irrespective of the amount of empirical evidence gathered in the support of one of these ideas or the other (Popper 1963, 1988). For example, to be "proven," a certain scientific law should account for *every single instance* of the phenomenon it purports to describe *at all times*. It can logically be argued that one such future instance, of which we have no knowledge whatsoever, may behave in a manner contrary to what the law states. As such, the law can never acquire an absolutely "proven" status. This equally holds in the case of hypotheses and theories. This philosophical aside, while not intended for inclusion with younger learners, can help highlight both the tentative nature of certain scientific knowledge and the durability of other knowledge as a function of the weight of empirical evidence.

Before moving on to specifically address the development, use, and interpretation of various NOS assessments, it is important to note that science educators and science education researchers often conflate NOS with science processes, practices, or scientific inquiry (SI). Although these aspects of science overlap and interact in important ways, it is nonetheless important to distinguish between them. Scientific processes are activities related to collecting and analyzing data and drawing conclusions (AAAS 1990, 1993; NRC 1996). For example, observing and inferring are scientific processes. More complex than individual processes, scientific inquiry involves various science processes used in a cyclical manner. On the other hand, NOS refers to the epistemological underpinnings of the activities of science and the characteristics of the resulting knowledge. As such, realizing that observations are necessarily theory-laden and are constrained by our perceptual apparatus belongs within the realm of NOS. Distinguishing NOS from SI for the purpose of providing focus to this chapter should in no way be construed to mean that NOS is considered more important for students to learn about. Certainly, NOS and SI, although different, are intimately related and are both important for students to understand, though making a distinction between NOS and SI is not meant to imply that the two constructs are distinct. Furthermore, there is much evidence that NOS is best taught within a context of SI or activities that are reasonable facsimiles of inquiry. That is, inquiry experiences provide students with foundational experiences upon which to reflect about aspects of NOS.

The conflation of NOS and SI has plagued research on NOS from the beginning. Hence, the reader will note that many NOS assessments are actually more focused on SI than NOS. These studies are nevertheless reviewed, rather than excluded, since they have become an accepted part of the history of research on assessment of NOS. The definition used by these studies for NOS is just not consistent with current usage of the construct. Again, the aspects of NOS presented here are not meant to be exhaustive, as other listings certainly exist. However, what has been presented is directly consistent both with what current reform documents state students should know about NOS and also with the perspective taken by an overwhelming majority of the research literature.

Lastly, and as has been communicated previously, NOS can be a moving target, as it becomes clear to anyone who considers the works of Popper (1959), Kuhn (1962), Lakatos (1970), Feyerabend (1975), Laudan (1977), and Giere (1988) that perceptions of NOS are as tentative, if not more so, than scientific knowledge itself. NOS is, in effect, analogous to scientific knowledge. Some individuals, unfortunately, have dwelled too heavily on such differing perceptions (e.g., Alters 1997) without consideration of the overarching goal of research on improving conceptions of NOS. The recognition that our collective views of NOS have changed and will continue to change is not a justification for ceasing all NOS-related research until total agreement is reached or for avoiding recommendations or identifying what we think students should know. As educators, we have no difficulty including certain theories and laws within our science curricula even though we recognize that these may change in the near or distant future. What is important is that students understand the evidence for current beliefs about natural phenomena and are aware that evidence has similarly lead to our current beliefs about NOS. Just as with “traditional” subject matter, these perceptions may change as additional evidence is collected or the same evidence is viewed in a different way.

Regardless of the various “problems” associated with reaching consensus on specific aspects of NOS, and issues created by the tentativeness of the construct itself, NOS has been the object of systematic educational research for approximately 60 years. While there have been numerous reviews of research related to the teaching, learning, and assessment of nature of scientific knowledge (e.g., Abd-El-Khalick and Lederman 2000; Lederman 1992, 2007; Meichtry 1992), this review will focus on assessment of NOS. For practical reasons, the research reviewed is restricted to published reports and to those studies with a primary focus on NOS and to those assessments that have at least attempted to establish validity and/or reliability.

29.4 Assessing Conceptions of NOS

The development and assessment of students’ and teachers’ conceptions of nature of scientific knowledge has been a concern of science educators for nearly 60 years and arguably constitutes a line of research in its own right. Although there have been numerous criticisms of the validity of various assessment instruments over the years, students' and teachers' understandings have consistently been found lacking. This consistent finding, regardless of assessment approach, supports the notion that student and teacher understandings are not at the desired levels.

The history of assessment of NOS mirrors the changes that have occurred in both psychometrics and educational research design over the past few decades. The first formal assessments, beginning in the early 1960s, emphasized quantitative approaches, as was characteristic of the overwhelming majority of science education research investigations. Prior to the mid-1980s, with few exceptions, researchers were content to develop instruments that allowed for easily "graded" and quantified measures of individuals' understandings. In some cases, standardized scores were derived. Within the context of the development of various instruments, some open-ended questioning was involved in construction and validation of items. More recently, emphasis has been placed on providing an expanded view of an individual's knowledge regarding NOS. In short, in an attempt to gain more in-depth understandings of students' and teachers' thinking, educational researchers have resorted to the use of more open-ended probes and interviews. The same has been true with the more contemporary approaches to assessment related to NOS. Unfortunately, and in accordance with the pressures of high-stakes testing, momentum appears to be building for a return to more quantitative measures of NOS, which allows for large-scale administration and assessment of students' and teachers' understandings. In addition to this shift back to more "traditional" assessments, the *Next Generation Science Standards* (NRC 2011) in the USA are improvements over the original but, by a large degree, still ignore the long-standing empirical research on NOS, equating the "doing of science" with developing understandings about NOS. Consequently, the resulting assessment is likely not to be a valid measure of what has been known as NOS.

Although critical evaluations of assessment instruments have been provided elsewhere (Lederman 2007; Lederman et al. 1998), the purpose here is to summarize the various instruments and identify trends in the assessment of NOS. Table 29.1 presents a comprehensive list of the more formal instruments constructed and validated to assess various aspects of NOS. Most of the instruments address only certain aspects of NOS and often inappropriately confuse the issue by addressing areas other than NOS, including science process skills and attitudes toward science. Instruments considered to have poor validity have the following characteristics:

1. Most items concentrate on a student's ability and skill to engage in the process of science (e.g., to make a judgment and/or interpretation concerning data).
2. Emphasis is on the affective domain (the realm of values and feelings) rather than knowledge (i.e., over 50 % of items deal with attitude toward or appreciation of science and scientists).
3. Primary emphasis is placed upon "science as an institution" with little or no emphasis placed upon the epistemological characteristics of the development of scientific knowledge.

As mentioned before, the validity of many of these instruments is questionable because their primary focus is on areas beyond the scope of "nature of scientific knowledge." Those instruments with questionable validity (as measures of NOS) include the Science Attitude Questionnaire (Wilson 1954); Facts About Science

Table 29.1 Nature of science instruments

Date	Instrument	Author(s)
1954	Science Attitude Questionnaire	Wilson
1958	Facts About Science Test (FAST)	Stice
1959	Science Attitude Scale	Allen
1961	Test on Understanding Science (TOUS)	Cooley and Klopfer
1962	Processes of Science Test	BSCS
1966	Inventory of Science Attitudes, Interests, and Appreciations	Swan
1967	Science Process Inventory (SPI)	Welch
1967	Wisconsin Inventory of Science Processes (WISP)	Scientific Literacy Research Center
1968	Science Support Scale	Schwirian
1968	Nature of Science Scale (NOSS)	Kimball
1969	Test on the Social Aspects of Science (TSAS)	Korth
1970	Science Attitude Inventory (SAI)	Moore and Sutman
1974	Science Inventory (SI)	Hungerford and Walding
1975	Nature of Science Test (NOST)	Billeh and Hasan
1975	Views of Science Test (VOST)	Hillis
1976	Nature of Scientific Knowledge Scale (NSKS)	Rubba
1978	Test of Science-Related Attitudes (TOSRA)	Fraser
1980	Test of Enquiry Skills (TOES)	Fraser
1981	Conception of Scientific Theories Test (COST)	Cotham and Smith
1982	Language of Science (LOS)	Ogunniyi
1987	Views on Science-Technology-Society (VOSTS)	Aikenhead, Ryan, and Fleming
1990	Views of Nature of Science A (VNOS-A)	Lederman and O'Malley
1992	Modified Nature of Scientific Knowledge Scale (M-NSKS)	Meichtry
1995	Critical Incidents	Nott and Wellington
1998	Views of Nature of Science B (VNOS-B)	Abd-El-Khalick, Bell, and Lederman
2000	Views of Nature of Science C (VNOS-C)	Abd-El-Khalick, and Lederman
2002	Views of Nature of Science D (VNOS-D)	Lederman and Khishfe
2004	Views of Nature of Science E (VNOS-E)	Lederman and Ko
2006	Student Understanding of Science and Scientific Inquiry (SUSSI)	Liang et al.

Test (Stice 1958); Science Attitude Scale (Allen 1959); Processes of Science Test (BSCS 1962); Inventory of Science Attitudes, Interests, and Appreciations (Swan 1966); Science Support Scale (Schwirian 1968); Test on the Social Aspects of Science (Korth 1969); Science Attitude Inventory (Moore and Sutman 1970); Science Inventory (Hungerford and Walding 1974); Test of Science-Related Attitudes (Fraser 1978); the Test of Enquiry Skills (Fraser 1980); and the Language of Science (Ogunniyi 1982). Recently, Allchin (2012) proposed a prototype to assess what he called "whole science," but the instrument was never fully developed and it clearly conflated NOS with scientific inquiry. Hence, it is not discussed further here.

The remaining instruments have generally been considered to be valid and reliable measures of NOS by virtue of their focus on one or more ideas that have been traditionally considered under the label of "nature of scientific knowledge," as well as their reported validity and reliability data. These instruments have been used in numerous studies, and even the more traditional instruments (e.g., TOUS) continue to be used even though there is a significant movement away from such types of paper-and-pencil assessments. The validity of some of the assessment instruments listed and briefly described below has been justifiably criticized in the past few years. However, they are presented here as being the most valid (in terms of assessment focus) attempts to assess understandings of NOS using a written response format. What follows is a brief discussion of each instrument.

29.4.1 Test on Understanding Science (TOUS)

This instrument has been the most widely used assessment tool in NOS research (Cooley and Klopfer 1961). It is a four-alternative, 60-item multiple-choice test. In addition to an "overall" or "general" score, three subscales can be scored regarding understandings about (I) the scientific enterprise, (II) the scientist, and (III) the methods and aims of science. During the past few decades, the content of the *TOUS* has been criticized and has fallen into disfavor.[3]

29.4.2 Wisconsin Inventory of Science Processes (WISP)

The WISP consists of 93 statements that the respondent evaluates as "accurate," "inaccurate," or "not understood." However, in scoring the exam, "inaccurate" and "not understood" responses are combined to represent the opposite of "accurate." The WISP was developed and validated for high school students (Scientific Literacy Research Center 1967). Although this instrument has excellent validity and reliability data, a few concerns should be considered prior to its use. Of primary concern is its length. The 93-item test takes over an hour to administer, which precludes it from use in a single class period. In addition, this instrument does not possess discrete subscales, which, unfortunately, means that only unitary scores can be calculated.

29.4.3 Science Process Inventory (SPI)

This instrument is a 135-item forced-choice inventory (agree/disagree) purporting to assess an understanding of the methods and processes by which scientific knowledge evolves (Welch 1967; Welch and Pella 1967–1968). The content of the

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[3] See Aikenhead (1973), Hukins (1963), Welch (1969), and Wheeler (1968), among others.

SPI is almost identical to that of WISP and TOUS subscale III. The validation of the SPI was achieved in the usual manner for such instruments: literature review, devising a model, employing the judgment of "experts," getting feedback from pilot studies, and testing the instrument's ability to distinguish among different groups of respondents. The length (135 items) is a concern as well as its forced-choice format. Students are unable to express "neutral" or uncertain answers. Finally, like the WISP, the SPI does not possess subscales.

29.4.4 Nature of Science Scale (NOSS)

This instrument was developed to determine whether science teachers have the same view of science as scientists (Kimball 1968). It consists of 29 items to which the respondent may "agree," "disagree," or register a "neutral" response. Kimball's model of NOS is based upon the literature of the nature and philosophy of science and is consistent with the views of Bronowski (1956) and Conant (1951). The specific content of the NOSS was validated by nine science educators who judged whether the items were related to the model. The development, validation, and reliability measures were carried out with college graduates. Thus, it lacks reliability and validity data with respect to high school populations. Another concern is that the instrument lacks subscales and is, therefore, subject to the same criticism as any other unitary measure of the nature of scientific knowledge.

29.4.5 Nature of Science Test (NOST)

This instrument consists of 60 multiple-choice items addressing the following components of NOS: assumptions of science (8 items), products of science (22 items), processes of science (25 items), and ethics of science (5 items) (Billeh and Hasan 1975). The test consists of two types of items. The first type measures the individual's knowledge of the assumptions and processes of science and the characteristics of scientific knowledge. The second type of question presents situations that require the individual to make judgments in view of his/her understanding of NOS. The major shortcoming of this instrument is not its content, but, rather, that no subscales exist. Again, only a global or unitary score can be calculated.

29.4.6 Views of Science Test (VOST)

This instrument was developed specifically to measure understanding of the tentativeness of science (Hillis 1975). It consists of 40 statements that are judged to imply that scientific knowledge is either tentative or absolute. Respondents express their agreement with either view using a five-option Likert scale response format.

29.4.7 Nature of Scientific Knowledge Scale (NSKS)

This instrument is a 48-item Likert scale response format consisting of five choices (strongly agree, agree, neutral, disagree, and strongly disagree) (Rubba 1976). The test is described as an objective measure of secondary students' understanding of NOS. The NSKS and its subscales are based upon the nine factors of NOS specified by Showalter (1974). Rubba (1976) listed these nine factors as tentative, public, replicable, probabilistic, humanistic, historic, unique, holistic, and empirical. He noted a certain amount of shared overlap between the factors and proceeded to collapse them into a six-factor or six-subscale model of the nature of scientific knowledge. These six factors are amoral, creative, developmental (tentative), parsimonious, testable, and unified. The instrument was developed, validated, and found to be reliable for high school level students. The five-option Likert scale response format affords maximum freedom of expression to the respondent. The *NSKS* has generally been viewed positively by the research community; however, there is reason for some concern about its face validity. Many pairs of items within specific subscales are identical, except that one item is worded negatively. This redundancy could encourage respondents to refer back to their answers on previous, similarly worded items. This cross-checking would result in inflated reliability estimates which could cause erroneous acceptance of the instrument's validity.

29.4.8 Conceptions of Scientific Theories Test (COST)

The structure of this instrument was dictated by the developers' concern that previously existing instruments were based on single (supposedly enlightened) interpretations of NOS (Cotham and Smith 1981). Thus, the COST supposedly provides for nonjudgmental acceptance of alternative conceptions of science. The instrument is an attitude inventory consisting of 40 Likert scale items (with four options) and four subscales, each corresponding to a particular aspect of scientific theories. These include (I) ontological implications of theories, (II) testing of theories, (III) generation of theories, and (IV) choice among competing theories. The COST provides a theoretical context for four-item sets by prefacing each set with a brief description of a scientific theory and some episodes drawn from its history. The items following each theory description refer to that description. The four theoretical contexts are (1) Bohr's theory of the atom, (2) Darwin's theory of evolution, (3) Oparin's theory of abiogenesis, and (4) the theory of plate tectonics. A fifth context contains items that refer to general characteristics of scientific theories and is, therefore, not prefaced by a description. Two concerns must be addressed prior to using COST as an instrument to assess high school students' understandings of NOS. The first of these is the cognitive level of the instrument. It was designed for teachers and validated with undergraduate college students. The four theory descriptions used to provide context for the items are presented at a level that may be above the capabilities of many high school students.

A second concern with the COST instrument rests with the authors' claim that it, as opposed to all extant instruments, is sensitive to alternative conceptions of science. However, the authors actually specify which subscale viewpoints are consistent with a tentative and revisionary conception of science. Thus, although they claim to place no value judgments upon the various conceptions of science, Cotham and Smith actually do just that by linking certain viewpoints to the "highly prized" tentative and revisionary conception of scientific knowledge.

29.4.9 Views on Science-Technology-Society (VOSTS)

The VOSTS was developed to assess students' understanding of nature of scientific knowledge, technology, and their interactions with society (Aikenhead et al. 1987). It consists of a "pool" of 114 multiple-choice items that address a number of science-technology-society (STS) issues. These issues include Science and Technology, Influence of Society on Science/Technology, Influence of Science/Technology on Society, Influence of School Science on Society, Characteristics of Scientists, Social Construction of Scientific Knowledge, Social Construction of Technology, and Nature of Scientific Knowledge. The VOSTS was developed and validated for grades 11 and 12 students. A fundamental assumption underlying the development of this instrument was that students and researchers do not necessarily perceive the meanings of a particular concept in the same way. Aikenhead and Ryan (1992) recognized the importance of providing students with alternative viewpoints based upon student "self-generated" responses to avoid the "constructed" responses offered by most of the previous nature of scientific knowledge assessment instruments. Unlike most other instruments, the VOSTS does not provide numerical scores; instead it provides a series of alternative "student position" statements. Extensive work was done on the careful validation of the instrument over a period of 6 years.

29.4.10 Views of Nature of Science, Form A (VNOS-A)

In an attempt to ameliorate some of the problems that each of the seven items focused on different aspects of tentativeness noted by Aikenhead et al. (1987) during the development of the VOSTS and those noted in the use of the NSKS (Rubba 1976) relative to the use of paper-and-pencil assessments, Lederman and O'Malley developed an open-ended survey consisting of seven items (Lederman and

O'Malley 1990). This instrument was designed to be used in conjunction with follow-up interviews and in science. Several problems were noted in the wording of some of the questions, resulting in responses that did not necessarily provide information on students' views of "tentativeness." The authors claimed that follow-up interviews alleviated this problem.

29.4.11 Modified Nature of Scientific Knowledge Scale (M-NSKS)

This instrument is a modified NSKS instrument with 32 statements from four of the NSKS subscales (Meichtry 1992). These subscales are (I) creative, (II) developmental, (III) testable, and (IV) unified. M-NSKS was developed, with reliability and validity reported, for use with 6th, 7th, and 8th graders.

29.4.12 Critical Incidents

The use of "critical incidents" to assess teachers' conceptions of NOS was a significant departure from the usual paper-and-pencil assessment (Nott and Wellington 1995). In particular, Nott and Wellington are of the opinion that teachers do not effectively convey what they know about nature of scientific knowledge in "direct response to abstract, context-free questions of the sort, 'What is science?'" (Nott and Wellington 1995). Instead, they created a series of "critical incidents" that are descriptions/scenarios of actual classroom events. Teachers are expected to respond to the incidents by answering the following three questions: (1) What would you do?, (2) What could you do?, and (3) What should you do? Although the use of critical incidents appears to be an excellent instructional tool to generate meaningful discussions in preservice and in-service courses, whether the teachers' responses are related to their views about NOS is still questionable. In short, the approach is based on the assumption that teachers' views of NOS automatically and necessarily influence classroom practice, an assumption that is simply not supported by the existing literature.

29.4.13 Views of Nature of Science B, C, D, E (VNOS-B, VNOS-C, VNOS-D, VNOS-E)

This series or buffet of instruments has stemmed from the same research group and was meant to be variations and improvements upon the original VNOS-A (Lederman and O'Malley 1990). In particular, each instrument contains open-ended questions that focus on various aspects of NOS with the differences being either the additional context-specific questions in forms B and C or the developmental appropriateness and language of VNOS-D. From a practical standpoint, VNOS-B and VNOS-C are too lengthy to be administered easily during a regular class period. Consequently, VNOS-D and VNOS-E were created with the aid of focus groups of secondary ($n = 10$) and elementary ($n = 10$) teachers and their students. The resulting instruments are easily administered in less than one hour and yield the same results as the longer VNOS-B and VNOS-C. VNOS-E is the most recently developed instrument and it has been designed for very young students (grades K-3). The items can also be used with students that cannot read or write (using a focus group format), and it represents the first measure of NOS designed for such a young audience.

29.4.14 Student Understanding of Science and Scientific Inquiry (SUSSI)

This instrument was developed, as was the case with the majority of standardized, quantitative approaches to assessing NOS, to overcome the time constraints and provide a potential tool for large-scale assessments (Liang et al. 2006). The SUSSI targets tentativeness, observations and inferences, subjectivity, creativity, social and culturally embeddedness, theories and laws, and scientific methods. Extensive evidence for the validity of the SUSSI is provided by its authors. The SUSSI is a combination of four Likert-scaled items followed by an open-response question similar in nature to the VNOS. As such, the SUSSI does not alleviate the time constraints associated with scoring the VNOS or similar instruments yet complicates the development of individual profiles of NOS understandings by introducing issues regarding interpretation of quantitative results and understandings of NOS. The SUSSI does not appear to be capable of providing meaningful inferences at the grain size that their developers intend. Although offering a means to utilize inferential statistics to assess instructional interventions, the guidelines for interpreting these quantitative data, and how the results of the two components of the questionnaire (i.e., Likert and free response) are "married," are not clearly explicated.

29.5 Development of Assessments for NOS

It should go without saying that any assessment instrument for NOS, or anything for that matter, should go through a systematic and extensive process for the establishment of both validity and reliability. Unfortunately, this has not been the case during the more than 50 years of assessment development. The establishment of reliability of any assessment is a fairly straightforward process; however, the establishment of validity is more complicated than most consider it to be. Simply gathering a group of "experts" together to chime in on whether the assessment items measure what the assessment developer intends is not the whole story. Pursuing construct validity in addition to the aforementioned content validity does not complete the picture either. The context and the target audience for the assessment are critical for any assessment. This has been an area in need of much attention. In specific, researchers would be better served by focusing on what is appropriate for K-12 students to know and be able to do, in contrast to arguing about why "lists" of outcomes or outcomes derived from others than scientists are anathema.[4]

29.5.1 Why Can't We Agree to Disagree?

Far too much discussion and journal pages have focused on the lack of consensus on a definition or characterization of NOS. In short, scholars would rather argue about the need to reach consensus before an assessment of NOS can be developed. Why is NOS held to a higher standard than other content in science? How many of the concepts and ideas in science have achieved absolute consensus before we attempt to teach them to students and assess what they have learned? As previously discussed, when one considers the developmental level of the target audience (K-12 students), the aspects of NOS stressed herein are at a level of generality that is not at all contentious. Nevertheless, if one is not willing to let go of the idea that the various aspects of NOS lack consensus and that assessment of NOS is, therefore, problematic, the "problem" is easily handled. One's performance on a NOS assessment can simply be used to construct a profile of what the student knows/believes about scientific knowledge. In terms of the aspects of NOS to be assessed, there is no reason to require that all assessments measure the exact same understandings. If the focus is just upon the assessment of understandings that are considered to be important for scientifically literate individuals to know, then there is no reason to require an agreed upon domain of NOS aspects. Different assessments may stress, to one degree or another, different aspects of NOS. This is no different than assessing students' understandings of the human heart. Different valid and reliable assessments stress and include different structures.

29.5.2 What Is So Bad About Lists?

Many researchers point out that lists are problematic (e.g., Allchin 2012; Matthews 2012), but lists serve an important function as they help provide a concise organization of the often complex ideas and concepts they include. Each item on a list is just a label or symbol for a much more in-depth and detailed elaboration. If "tree" is included in a list, it is simply a referent for all the structures and process that are involved in what is involved in being a "tree." There is the temptation to think that

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[4] As evidenced in Allchin (2012), Duschl and Grandy (2012), Irzik and Nola (2011), and Wong and Hodson (2009, 2010), among others.

lists are defined as consisting of very short (1–2 word) entries. There are numerous science education reform documents that specify and delineate what students should know and be able to do (i.e., standards). These are also lists of learning outcomes, even though the standards can be as long as a paragraph. The only problem with a list is how it is often used. If students are asked to simply and mindlessly memorize the list, then there is a problem. But, the problem is with pedagogy and not with the list. Irzik and Nola (2011) claim to have produced a depiction of NOS that is much more informative and comprehensive than a list. However, it is no different than a list. Their outcomes are formatted as a matrix as opposed to a linear format, but it is still a list.

Other researchers, most notably Duschl and Grandy (2012), label these "Consensus-based Heuristic Principles" as out-of-date and too general, in contrast to their "scientific practices in domain-specific contexts." Their description of how these lists are used unfortunately not consistent with the way they are intended to guide classroom practice, and it is difficult to image a thoughtful teacher using the aspects of nature of science in the manner assumed by Duschl and Grandy. On the contrary, the researchers criticized by Duschl and Grandy (e.g., Abd-El-Khalick 2012; Lederman et al. 2002; Niaz 2009) strongly advocate NOS as an overarching instructional theme that permeates not simply a single activity but hopefully an entire school science curriculum.

29.5.3 Knowing Versus Doing

There has been a perennial problem with developing assessments of nature of science that is connected to the research literature. All too often assessments include students' performance or inquiry skills/procedures within instruments on NOS. In spite of over a half century of research on NOS, some science education researchers (Allchin 2011, 2012) continue to conceptualize NOS as a skill as opposed to knowledge and espouse the belief that engagement in the practices of science is sufficient for developing understandings of NOS. The view that NOS is a skill, thus conflating it with scientific inquiry, minimizes the importance of understanding both of these constructs and their related characteristics and further obfuscates their associated nuances and interrelationships. Moreover, this view is not consistent with the National Science Education Standards (NRC 1996) and the Benchmarks for Science Literacy (AAAS 1993), which both describe NOS as knowledge, or the NRC's Framework for K-12 Science Education (NRC 2011). While focusing on scientific inquiry, the Benchmarks stress that students should develop understandings about SI beyond the ability to do SI, as this understanding is sine qua non to being scientifically literate, as is the case for understandings of NOS. Unfortunately the Next Generation Science Standards (NGSS) derived from the new framework are not so clear regarding their "vision" for promoting understandings of NOS. Although aspects such as tentativeness, creativity, and subjectivity in science are included in the framework, no clear distinction is made in the NGSS regarding how NOS explicitly fits into the crosscutting themes.

NOS has been a central theme underling science reforms since the 1950s for a good reason: NOS understandings (irrespective of how these are defined at the time of reform) are central to scientific literacy because NOS is metacognitive knowledge about science. Almost every other meaningful theme underlying past reform documents, such as AAAS Benchmark, NRC Standards, and NSTA Framework, appear in the NGSS, but the same cannot be said for NOS. This exclusion is simply not justified, nor is it justifiable. Unfortunately, regarding assessments of NOS, we may indeed be heading forward…into the past.

The conflation described is inherently linked to the assumption that NOS is learned by having students DO science. That is, if students are involved in authentic scientific investigations, they will also come to an understanding about NOS. The empirical research has consistently shown this assumption to be false for the past three decades (Lederman 2007). Clearly, students' ability to DO science is an important educational outcome, but it is not the same as having students reflect on what they have done. In terms of developing assessments of NOS, there must be a more concerted effort to realize that NOS is a cognitive outcome, not a "performance" outcome.

Related to this last issue is that a small minority of individuals (e.g., Sandoval 2005) insist that students' and teachers' understandings of NOS are best assessed through observations of behavior during inquiry activities (i.e., knowledge in practice). The literature clearly documents the discrepancies that often exist between one's beliefs/knowledge and behavior. More concretely, if an individual believes that scientific knowledge is tentative (subject to change) and another individual believes the knowledge to be absolute/static, how would this be evident in their behavior during a laboratory activity? If a student recognizes that scientific knowledge is partly subjective, how would this student behave differently during a laboratory investigation than a student with differing beliefs? This assessment approach adds an unnecessary layer of inference to one's research design. In the end, we must not forget that NOS is a cognitive outcome, not a behavior as some continue to insist (Allchin 2012). Hence, understandings of NOS are not appropriately assessed through observation of behaviors.

29.6 Uses and Interpretations of NOS Assessments

29.6.1 How Should Assessments Be Used?

Over the history of research on NOS, assessments have been primarily used as summative as opposed to formative assessments. There are few studies that make a systematic attempt to use assessment results to guide the development and enactment of instructional strategies related to NOS. The literature is replete with studies indicating that teachers and students do not possess what are considered adequate conceptions of NOS. It is safe to say that the research community can accurately predict what kinds of understandings teachers and students have about

NOS prior to instruction. Hence, the field needs to move forward and focus more attention on specific strategies to improve conceptions and to assess progressions of understandings, over time, from less to more sophisticated understandings. Unfortunately, there remains a consistent perceived need by researchers to develop an assessment instrument that can be administered to the masses in a short period of time and scored just as easily. Within all of us, it appears, is an "inherent" need to make our lives easier. Interviews and open-ended assessments are time-consuming to conduct and score. However, a quick perusal of recent programs from the Annual Meeting of the National Association for Research in Science Teaching indicates that the desire to create an instrument that can be mass administered and scored in a short period of time or allows for efficient scoring of existing ones continues (e.g., Abd-El-Khalick et al. 2012). Again, what is driving this approach is the perceived need for a more efficient summative assessment. Overall, we must not forget the current needs of researchers and the uses of assessments. It does not appear that there is a warranted need or justification for more traditional paper-and-pencil assessments of NOS.

29.6.2 The Devil Is in the Details: Interpreting the Data We Collect

Much has been said in this chapter about the problems with "traditional" paper-and-pencil assessments of an individual's understanding of NOS. One solution has advocated more open-ended questions followed by interviewing of respondents. Naturally, this approach directly contradicts the desire by some researchers to have easily administered and scored assessments. Although not a new insight, Lederman and O'Malley's (1990) investigation clearly highlighted the problem of paper-and-pencil assessments. They documented discrepancies between their own interpretations of students' written responses and the interpretations that surfaced from actual interviews of the same students. This unexpected finding (i.e., the purpose of the interviews was to help validate the paper-and-pencil survey that was used) was quite timely, as it occurred when educational researchers were making a serious shift toward more qualitative, open-ended approaches to assess individuals' understanding of any concept. Although the VNOS-A was created to avoid some of the concerns about "traditional" assessments (as were the subsequent series of VNOS forms), the problem of researchers interpreting responses differently than intended by the respondent remains to this day. The problem exists at all age levels (K-adult), with increasing levels of uncertainty as the age of the respondent decreases. It is for this reason that researchers should not abandon the interviewing of individuals about their written responses. Consequently, a clear issue when it comes to assessment of such complex constructs as NOS is that we get the most valid data possible. Just using paper-and-pencil assessments increases the possibility of a misinterpretation of respondents' understandings. In summary, the issue of using interviews as part of one's assessment of NOS is relevant to the development, use, and interpretation of assessments.

There has been an ongoing debate about the scoring and representation of data on understandings of NOS. In the early history of assessment development (i.e., 1960–1980), there were strong concerns about the bias inherent in each instrument (Cotham and Smith 1981; Lederman 2007). In particular, the value given to particular responses was directly related to whether the respondent held a view consistent with one philosophical view or another. Given the ever changing conceptualization of the construct NOS (Lederman 1992), many were concerned that scoring responses as if they were correct or incorrect was inappropriate. The solution to this problem was fairly easy, as the "scores" could simply be used to construct a profile of what an individual believes as opposed to a measure of whether they had an informed view of NOS. This approach seems valid, but it ignores the reality that educational systems have goals that specify what we want students to know. Even though conceptions of NOS may change (as is true with any science knowledge), at any point in time, we have an understanding we want our students to develop. In short there are "correct" and "incorrect" answers. Some profiles are more acceptable than others.

Perhaps a more important problem with interpretation is whether it is more accurate to develop numerical scores to represent what an individual knows or whether to develop profiles and then categorize the profiles as informed, naïve, etc. Numerical values allows for easy statistical analysis, but as with any numerical value assigned to a complex construct, much information is lost if we simply have a number. Consequently, it seems wise to have rich descriptions of what individuals know and how this knowledge becomes more or less sophisticated as opposed to simply providing a numerical value.

29.7 What a Long and Tortured Journey This Has Been

Research on students' and teachers' understandings of NOS has been pursued in earnest since 1957 (Mead and Métraux 1957). Naturally, an assortment of assessments for NOS has been developed to support this long line of research. The first assessment was rather informal with the most formalized, even standardized, assessment (i.e., TOUS) appearing in 1961 (Cooley and Klopfer 1961). This review, and others, clearly has shown that assessments of NOS began as more traditional convergent paper-and-pencil tests and then slowly transitioned to the use of more open-ended questionnaires that provide respondents more freedom to express their views. Finally, the past two decades have been characterized by open-ended questionnaires followed by interviews. The interviews, it is believed, help to clarify respondents' written answers as well as avoid some of the problems associated with researchers' misinterpretations of respondents' written answers. Although this chapter is focused on assessment, the discussion of assessment is inextricably connected to the scholarship on NOS, its conceptualization, instructional approaches, etc. As such and as long as this assessment journey has been, we are at a crossroad that threatens to transform assessments into tools that are irrelevant to the question at hand, namely, measuring K-12 students' and teachers' understandings of NOS.

Only a summary of the most critical issues facing NOS assessments discussed in this chapter will be highlighted here. Because of the inextricable link between assessments and the body of research on NOS understandings, these same issues are relevant to the direction of future research as well.

29.7.1 NOS Is a Cognitive Outcome, Not a Behavior

NOS is often confused with, or combined with, scientific inquiry (SI). NOS refers to characteristics of scientific knowledge and SI refers to what scientists do to develop scientific knowledge. Both are clearly important, but assessments of knowledge are different than assessments of performance behaviors, and we know from volumes of research that it is quite difficult to infer knowledge from behavior. Some of the current efforts to assess NOS knowledge based on students' performance of laboratory activities and participation in argumentation about ideas are a step backwards, and they ignore the results of over 50 years of empirical research. NOS is a complex construct that does not lend itself to easily administered and scored assessments.

Although this has been recognized by the trends we have seen over the years in how NOS is assessed, there is a continued desire to develop assessments that are convergent, easily administered to large samples, and easily scored. Moving in this direction is another step backwards. Is the goal expediency or accurately assessing what students and teachers know?

29.7.2 Do Not Lose Sight of the Target Audience, K-12 Students and Teachers

There is a continuing debate about "whose NOS we are measuring." This discussion began with Alters (1997), and it continues with the recent writings of Wong and Hodson (2009, 2010). In the end, the argument always rests on the voice of scientists, and how what they think is important regarding NOS is not being heard or used. Actually, the international reform documents specifying outcomes regarding NOS have had strong input from the scientific community. More importantly, the audience for which these outcomes have been specified is the consumers of science, not scientists. We need to continually remind ourselves for whom the NOS outcomes have been written. What has been specified is not directed at scientists, historians, or philosophers. The knowledge specified is what is considered important for the attainment of scientific literacy by the general citizenry. To dissect the construct of NOS down to its very esoteric levels reveals a construct that is far too abstract for the general public. This really is no different than why we do not expect all high school graduates to understand the most in-depth aspects of the dark reactions of photosynthesis.

There is little doubt that the arguments described in this chapter will continue. At times it appears that our goal in academia is more about the debate than the purpose we are trying to accomplish. It is not all productive to argue about what should be included under the rubric of SI and NOS. It makes little sense to argue about whether lists are good or bad. The focus of our attention should always be on what we consider important for students and teachers and the general public to know, not the label we put on the knowledge. And when we consider the knowledge to be known and assessed, let us not forget the audience, their emotional and cognitive developmental levels, and their needs as citizens.

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Chapter 30
New Directions for Nature of Science Research

Gürol Irzik and Robert Nola

30.1 Introduction

Calls for the inclusion of the nature of science (NOS for short) into science education have a long history. A number of distinguished scientists, philosophers and education theorists such as John Dewey, James Conant, Gerald Holton, Leo Klopfer, Joseph Schwab, James Robinson, James Rutherford, Michael Martin, Richard Duschl, Derek Hodson, Norman Lederman, Michael Matthews and Norman McComas throughout the twentieth century emphasised the importance of teaching science's conceptual structure and its epistemological aspects as part of science education (Matthews 1998a; McComas et al. 1998). Today, science education curriculum reform documents in many parts of the world underline that an important objective of science education is the learning of not only the content of science but its nature.[1] The rationale is that scientific literacy requires an understanding of the nature of science, which in turn facilitates students' learning of the content of science, helps them grasp what sort of a human enterprise science is, helps them appreciate its value in today's world and enhances their democratic citizenship, that is, their ability to make informed decisions, as future citizens, about a number of controversial issues such as global warming, how to dispose nuclear waste, genetically modified food and the teaching of

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[1] See, for example, American Association for the Advancement of Science (1990, 1993), Council of Ministers of Education (1997), National Curriculum Council (1988), National Research Council (1996), Rocard et al. (2007), and McComas and Olson (1998).

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intelligent design in schools.[2] Allchin expressed this idea succinctly: 'Students should develop an understanding of how science works *with the goal of interpreting the reliability of scientific claims in personal and public decision making*' (Allchin 2011, p. 521; emphasis original).

There is a voluminous literature on what NOS is, how to teach it and what views of NOS students and teachers hold. The aim of this chapter is not to review this literature. The interested reader can refer to other chapters of this handbook and earlier useful surveys (Abd-El-Khalick and Lederman 2000; Deng 2011 and others; Lederman 2007). Teachers' and students' views of NOS are also beyond the scope of this chapter, in which we focus exclusively on what NOS is. In the next section we summarise the consensus NOS theorising in science education has produced. Making use of the existing consensus, we then provide, in Sect. 30.3, a structural description of all the major aspects of science in terms of eight categories. Applying the idea of family resemblance to these categories, we obtain what we call 'the family resemblance approach'. We articulate it in some detail in Sect. 30.5. We believe that the family resemblance approach provides a systematic and unifying account of NOS. We discuss this and other virtues of the family resemblance approach in Sect. 30.6. We end the chapter by making some suggestions about how to use this approach in the classroom.

We would like to emphasise that the present chapter does not deal with empirical matters such as what teachers and pupils might understand of NOS. Rather, our task is one within the theory of NOS: it is to provide a new way of thinking about what is meant by the 'nature of science'. Nevertheless, we do hope that theorists of science education and science teachers familiar with NOS discussions will find our approach not only theoretically illuminating but also pedagogically useful.

30.2 Consensus on NOS

NOS research in the last decade or so has revealed a significant degree of consensus amongst the members of the science education community regarding what NOS is and which aspects of it should be taught in schools at the precollege level. This consensus can be highlighted as follows.

Based on considerations of accessibility to students and usefulness for citizens, Lederman and his collaborators specified the following characteristics of NOS:

- Scientific knowledge is empirical (relies on observations and experiments).
- Is reliable but fallible/tentative (i.e. subject to change and thus never absolute or certain).
- Is partly the product of human imagination and creativity.

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[2] This point is commonly made, for example, in Driver et al. (1996), McComas et al. (1998), Osborne 2007, and Rutherford and Ahlgren (1990).

- Is theory-laden and subjective (i.e. influenced by scientists' background beliefs, experiences and biases).
- Is socially and culturally embedded (i.e. influenced by social and cultural context).[3]

They also emphasised that students should be familiar with concepts fundamental to an understanding of NOS such as observation, inference, experiment, law and theory and be also aware of the distinctions between observing and inferring and between laws and theories and of the fact that there is no single scientific method that invariably produces infallible knowledge. Others added that science is theoretical and explanatory; scientific claims are testable and scientific tests are repeatable; science is self-correcting and aims at achieving values such as high explanatory and predictive power, fecundity (fruitfulness), parsimony (simplicity) and logical coherence (consistency) (Cobern and Loving 2001; Smith and Scharmann 1999; Zeidler and others 2002).

A number of researchers propose a similar list of characteristics by studying the international science education standards documents. These documents also indicate substantial consensus on two further matters: the ethical dimension of science (e.g. scientists make ethical decisions, must be open to new ideas, report their findings truthfully, clearly and openly) and the way in which science and technology interact with and influence one another (McComas et al. 1998; McComas and Olson 1998). Based on a Delphi study of an expert group consisting of scientists, science educators and science communicators, philosophers, historians and sociologists of science, Osborne and others (2003) found broad agreement on the following eight themes:

- Scientific method (including the idea that continual questioning and experimental testing of scientific claims is central to scientific research)
- Analysis and interpretation of data (the idea that data does not speak by itself, but can be interpreted in various ways)
- (Un)certainty of science (i.e. scientific knowledge is provisional)
- Hypothesis and prediction (the idea that formulating hypotheses and drawing predictions from them in order to test them is essential to science)
- Creativity in science (the idea that since scientific research requires much creativity, students should be encouraged to create models to explain phenomena)
- Diversity of scientific thinking (the idea that science employs different methods to solve the same problem)
- The historical development of scientific knowledge (i.e. scientific knowledge develops historically and is affected by societal demands and expectations)
- The role of cooperation and collaboration in the production of scientific knowledge (i.e. science is a collaborative and cooperative activity, as exemplified by teamwork and the mechanism of peer review).

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[3] See Abd-El-Khalick (2004), Abd-El-Khalick and Lederman (2000), Bell (2004), Khishfe and Lederman (2006), Lederman (2004, 2007). Note that all of these characteristics pertain to scientific knowledge. For that reason, Lederman suggested replacing the phrase 'nature of science' with 'nature of scientific knowledge' in his recent writings (Lederman 2007).

Wong and Hodson (2009, 2010) came up with very similar themes (but with slightly different emphasis) on the basis of in-depth interviews with well-established scientists from different parts of the world who worked in different fields:

- Scientific method (different disciplines employ different methods of investigation)
- Creativity in science (creative imagination plays an important role in every stage of scientific inquiry from data collection to theory construction, and absolute objectivity in the sense of freeing oneself from biases completely is impossible)
- The importance of theory in scientific inquiry (scientific activity is highly theoretical)
- Theory dependence of observation (scientific data is theory laden and can be interpreted in various ways)
- Tentative nature of scientific knowledge (science does not yield certainty)
- The impact of cultural, social, political, economic, ethical and personal factors on science (such factors greatly influence the direction of scientific research and development and may cause biased results and misconduct) and the importance of cooperation, peer review and shared norms (such as intellectual honesty and open mindedness) in knowledge production

The overlap between the findings of these studies indicates a substantial consensus regarding NOS amongst education theorists. However, there has been some debate as to whether processes of inquiry (such as posing questions, collecting data, formulating hypotheses, designing experiments to test them) should be included in NOS. While Lederman (2007) suggested leaving them out, other science education theorists disagreed arguing that they constitute an inseparable part of NOS (Duschl and Osborne 2002; Grandy and Duschl 2007). Indeed, research summarised in the above two paragraphs do cite processes of inquiry as an important component of NOS.

Of course, much depends on how the various aspects and themes of NOS are spelled out. Osborne and his collaborators warn that various characteristics of NOS should not be taken as discrete entities, so they emphasise their interrelatedness (Osborne and others 2001, 2003, p. 711). In a similar vein, others note that blanket generalisations about NOS introduced out of context do not provide a sophisticated understanding of NOS (Elby and Hammer 2001; Matthews 2011); rather, the items within NOS ought to be elucidated in relation to one another in 'authentic contexts'. Accordingly, many science educators have called for 'an authentic view' of science, which aims to contextualise science and focuses on science-in-the-making by drawing either on science-technology-society (STS) studies or on the interviews with scientists themselves about their day-to-day activities; this underlines the heterogeneity of scientific practices across scientific disciplines through historical and contemporary case studies.[4]

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[4] See Ford and Wargo (2007), McGinn and Roth (1999), Rudolph (2000), Samarapungavan et al. (2006), Wong and Hodson (2009, 2010), and Wong et al. (2009).

A number of science education theorists also urged that issues arising from science-technology-society interactions, the social norms of science and funding and fraud within science all be allotted more space in discussions of NOS; a focus on these is especially pertinent when educating citizens who will often face making hard decisions regarding socio-scientific problems in today's democracies. These topics have been raised earlier in some detail (Aikenhead 1985a, b; Kolsto 2001; Zeidler and others 2002) and are receiving increasing attention in recent years, in line with calls for an authentic view of science.[5]

30.3 NOS Categories: A Structural Description

The consensus on NOS highlighted above reveals that science is a multifaceted enterprise that involves (a) processes of inquiry, (b) scientific knowledge with special characteristics, (c) methods, aims and values and (d) social, historical and ethical aspects. Indeed, science is many things all at once: it is an investigative activity, a vocation, a culture and an enterprise with an economic dimension and accordingly has many features (cognitive, social, cultural, political, ethical and commercial) (Weinstein 2008; Matthews 2011). What is needed then is a systematic and unifying perspective that captures not just this or that aspect of science but the 'whole science' (Allchin 2011). This is no easy task, and there is certainly more than one way of carrying it out. Our suggestion is to begin with a broad distinction between *science as a cognitive-epistemic system of thought and practice* on the one hand and s*cience as a social-institutional system* on the other. This distinction is actually implicit in the aspects of NOS expressed (a) through (d) above: science as a cognitive-epistemic system incorporates (a), (b) and (c), while science as a social-institutional system captures (d). We hasten to add that we intend this as an analytical distinction to achieve conceptual clarity, not as a categorical separation that divides one from the other. In practice, the two constantly interact with each other in myriad ways, as we will see.

30.3.1 Science as a Cognitive-Epistemic System

We spell out science as a cognitive-epistemic system in terms of four categories obtained by slightly modifying (a)–(c): processes of inquiry, aims and values, methods and methodological rules and scientific knowledge. We explain these categories briefly below.[6]

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[5] See Sadler (2011), Weinstein (2008), Wong and Hodson (2010), Zemplen (2009); see also the special issue of the journal *Science & Education* vol. 17, nos. 8–9, 2008.

[6] For a more detailed discussion of these, see Nola and Irzik (2005, Chaps. 2, 4, 6, 7, 8, 9, and 10).

30.3.1.1 Processes of Inquiry

This includes posing questions (problems), making observations, collecting and classifying data, designing experiments, formulating hypotheses, constructing theories and models and comparing alternative theories and models (Grandy and Duschl 2007).

30.3.1.2 Aims and Values

This will include items such as *prediction*, *explanation*, *consistency*, *simplicity* and *fruitfulness*; these are amongst the well-known aims of science recognised in the science education literature, as we saw in the previous section. With regard to prediction and explanation, we would like to make two points, which the science education literature tends to neglect. First, scientists value *novel* predictions more than other kinds of predictions because novel predictions of a theory give greater support to it than those that are not (Nola and Irzık 2005, pp. 245–247). (A prediction is novel if it is a prediction of a phenomenon that was unknown to the scientists at the time of the prediction.) Second, although there are different kinds of explanations and therefore different models of explanations, all scientific explanations are naturalistic in the sense that natural phenomena are explained in terms of other natural phenomena, without appealing to any supernatural or occult powers and entities (Lindberg 1992, Chap. 1; Pennock 2011).[7]

Other aims of science include the following: *viability* (von Glasersfeld 1989), *high confirmation* (Hempel 1965, Part I), *testability* and *truth* or at least *closeness to truth* (Popper 1963, 1975) and *empirical adequacy* (van Fraassen 1980). Aims of science are sometimes called (cognitive-epistemic) values since scientists value them highly in the sense that they desire their theories and models to realise them (Kuhn 1977). Values in science can also function as shared criteria for comparing theories and be expressed as methodological rules. For example, we can say that given two rival theories, other things being equal, the theory that has more explanatory power is better than the one that has less explanatory power. Expressed as a methodological rule, it becomes, given two rival theories, other things being equal, *choose*, or *prefer*, the theory that is more explanatory. Similar rules can be derived from other values. These enable scientists to compare rival theories about the same domain of phenomena rationally and objectively (Kuhn 1977).

30.3.1.3 Methods and Methodological Rules

Science does not achieve its various aims randomly, but employs a number of methods and methodological rules. This point emerges clearly in many studies on NOS. Historically, there have been proposals about scientific method from Aristotle,

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[7] See Godfrey-Smith (2003) for a succinct summary of different models of explanations in science.

Bacon, Galileo, Newton to Whewell, Mill and Peirce, not to mention the many theories of method proposed in the twentieth century by philosophers, scientists and statisticians. For many of them, deductive, inductive and abductive reasoning form an important part of any kind of scientific method. Additional methods for testing hypotheses include a variety of inductive and statistical methods along with the hypothetico-deductive method (Nola and Sankey 2007; Nola and Irzık 2005, Chaps. 7, 8, and 9). The idea of scientific methodology also includes methodological rules; these have not received sufficient attention in the science education literature. Methodological rules are discussed at length by a number of philosophers of science such as Popper (1959) and Laudan (1996, Chap. 7). Here are some of them:

- Construct hypotheses/theories/models that are highly testable.
- Avoid making ad hoc revisions to theories.
- Other things being equal, choose the theory that is more explanatory.
- Reject inconsistent theories.
- Other things being equal, accept simple theories and reject more complex ones.
- Accept a theory only if it can explain all the successes of its predecessors.
- Use controlled experiments in testing casual hypotheses.
- In conducting experiments on human subjects, always use blinded procedures.

Two general points about scientific methods and methodological rules are in order. First, although they certainly capture something deep about the nature of methods employed in science, it should not be forgotten that they are highly idealised, rational constructions. As such, they do not faithfully mirror what scientists do in their day-to-day activities; nor can they always dictate to them what to do at every step of their inquiry. Nevertheless, they can often tell them when their moves are, or are not, rational and do explain (at least partially) the reliability of scientific knowledge. Second, we presented the above rules of method as if they are categorical imperatives. This needs to be qualified in two ways. The first is that some of the rules can, in certain circumstances, be abandoned. Spelling out the conditions in some antecedent clause in which the rules can be given up is not an easy matter to do; so such rules are best understand to be defeasible in unspecified circumstances. The second is that such categorical rules ought to be expressed as hypothetical imperatives which say: rule R ought to be followed if some aim or value V will be (reliably) achieved (see Laudan 1996, Chap. 7). Often reference to the value is omitted or the rule is expressed elliptically. For example, the rule about ad hocness has an implicit value or aim of high testability. So, more explicitly it would look like: ‘If you aim for high testability, avoid making *ad hoc* revisions to theories’. When rules are understood in this way, then the link between the methodological rules of category 3 and the aims of category 2 becomes clearly visible.

30.3.1.4 Scientific Knowledge

When processes of inquiry achieve their aims using the aforementioned methods and methodological rules, these processes culminate in some ‘product’, viz.

scientific knowledge. Such knowledge ‘end products’ are embodied in laws, theories and models as well as collections of observational reports and experimental data. Scientific knowledge is the most widely discussed category of NOS, as we have seen in the previous section.

30.3.2 Science as a Social-Institutional System

Science as a social-institutional system is investigated less than science as a cognitive-epistemic system, and for that reason it is harder to categorise. We propose to study it in terms of the following categories: professional activities, the system of knowledge certification and dissemination, scientific ethos and finally social values. We discuss them in some detail below, taking into account the findings of the NOS research on this topic indicated in Sect. 30.2.

As decades of science-technology-society studies have shown, science not only is a cognitive system but is, at the same time, both a cooperative and a competitive community practice that has its own ethos (i.e. social and ethical norms) and its own system of knowledge certification and dissemination. It is a constantly evolving social enterprise with intricate relationships with technology and with the rest of the society, which both influences and is influenced by it. Scientists form a tight community and are engaged in a number of professional activities, interacting both with each other and the larger public. In short, science is a historical, dynamic, social institution embedded within the larger society. Categories of science as social-institutional system can be described as follows.

30.3.2.1 Professional Activities

Scientists do not just carry out scientific research. Qua being scientists, they also perform a variety of professional activities such as attending academic meetings, presenting their findings there, publishing them, reviewing manuscripts and grant proposals, writing research projects and seeking funds for them, doing consulting work for both public and private bodies and informing the public about matters of general interest. In this way, they perform various cognitive-epistemic and social functions such as certifying knowledge and serving certain social goals. Whether they are engaged in cognitive-epistemic or professional activities, they are expected to conform to a number of social and ethical norms. We discuss these below.

30.3.2.2 The Scientific Ethos

Part of the meaning of the claim that science is a social institution is that it has its own social (institutional) and ethical norms, which refer to certain attitudes scientists are expected to adopt and display in their interactions with their fellow scientists as well as in carrying out their scientific activities. We call them 'the scientific ethos' (or, equivalently, 'the ethos of science') for convenience, a phrase coined by the famous sociologist of science Robert Merton. However, as we will see below, the scientific ethos as we understand it is not confined to what is known as the 'Mertonian norms' in the literature. Merton was one of the first to study the institutional norms of science in the 1930s and formulated some of them as follows, based on his extensive interviews with scientists (Merton 1973, Chap. 13):

- *Universalism*: Science is universal in the sense that scientific claims are evaluated according to pre-established objective, rational criteria so that characteristics of scientists such as ethnic origin, nationality, religion, class and gender are irrelevant when it comes to evaluation.
- *Organised scepticism*: Scientists subject every claim to logical and empirical scrutiny on the basis of clearly specified procedures that involve scientific reasoning, testability and methodology and suspend judgement until all the relevant facts are in and bow to no authority except that of critical argumentation.
- *Disinterestedness*: Scientists should evaluate and report their findings independently of whether they serve their personal interests, ideologies and the like. The norm of disinterestedness has the function of preventing scientists from hiding or fudging the results of their inquiries even when they go against their personal biases, interests and favoured ideology.
- *Communalism* refers to the common ownership of scientific discovery or knowledge. The rationale is that science is a cooperative endeavour: new scientific knowledge always builds upon old knowledge and that scientific discoveries owe much to open and free discussion and exchange of ideas, information, techniques and even material (such as proteins).

Although Merton arrived at these norms through an empirical study, we should not lose sight of the fact that they can be taken as both descriptive and prescriptive *qua* being norms. In other words, they tell us how scientists ought to behave, not just how they do behave when they do science. Their normative nature and power is evident from the fact that scientists often face the sanctions of the scientific community when they violate them.[8]

In time, the scientific community has become increasingly self-conscious of the norms of conduct in science, as a result of which they have proliferated and been codified under the banner 'ethical codes of conduct'. There is now a whole subfield called the 'ethics of science' devoted to this topic. Amongst other things, these norms include the following (Resnik 2007, Chap. 2):

- Intellectual honesty (or integrity): Scientists should not fabricate, distort or suppress data and should not plagiarise. They should bow to no authority except that of evidence and critical argumentation.

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[8] STS scholars are generally critical of Mertonian norms and claim that there is a counter-norm for every Mertonian norm, with the implication that Mertonian norms do not guide scientific practice and therefore are simply functionless. See, for example, Sismondo (2004, Chap. 3) and the literature cited therein. However, there are also excellent critiques of these critiques such as Radder (2010).

- Respect for research subjects: Scientists should treat human and animal subjects with respect and dignity. This involves getting the informed consent of human subjects and not inflicting unnecessary pain on animal subjects and the like.
- Respect the environment: Avoid causing harm to the environment.
- Freedom: Scientists should be free to pursue any research, subject to certain constraints (e.g. as implied by the previous two ethical principles).
- Openness: Scientists should be open to free and critical discussion and to share ideas, data, techniques and even materials (such as proteins). They should be willing to change their opinion when presented with good reasons.

Today many scientific institutions (universities, academies, funding organisations, etc.) have such ethical codes which they announce on their websites.

None of this is meant to suggest that there is no misconduct, fraud, data suppression or misrepresentation and the like, or fierce competition, especially for scarce resources such as funding, which sometimes results in secrecy (the opposite of openness) in science. Scientists are not saints. Nevertheless, when they violate the norms of science, they often face sanctions. Science has developed a social mechanism of certification and dissemination to eliminate or at least reduce misconduct and promote collaboration amongst scientists.

30.3.2.3 The Social Certification and Dissemination of Scientific Knowledge

When a scientist or a team of scientists completes their research, they are hardly finished with their work. Their findings need to be published; this requires a process of peer review. When published, they become public and are now open to the critical scrutiny of the entire community of relevant experts. Only when they prove their mettle during this entire ordeal are their findings accepted into the corpus of scientific knowledge and can, amongst other things, be taught at schools. This is in a nutshell the *social* system of certification and dissemination of scientific knowledge, which involves the collective and collaborative efforts of the scientific community (Kitcher 2011, Chap. 4). This system functions as an effective *social quality control* over and above the *epistemic control* mechanisms that include testing, evidential relations and methodological considerations described in Sect. 30.3.1. They jointly work to help reduce the possibility of error and misconduct.

30.3.2.4 Social Values of Science

Science embodies not only cognitive-epistemic values but also social ones. Some of the most important social values are freedom, respect for the environment and social utility broadly understood to refer to improving people's health and quality of life as well as to contributing to economic development. Without sufficient freedom of research, scientific development would be stifled. Respect for the environment involves both the negative duty of not damaging it and the positive duty of protecting it by saving biodiversity and reducing carbon emissions that cause climate change. As a species we are unlikely to survive if we do not respect the environment. Science that does not contribute to better lives for people would not enjoy their support; the social legitimation of science today depends crucially on its social utility. Social utility then serves as an important social goal of science.

This completes our description of the eight categories of science which can be tabulated as below.

Science							
Science as a cognitive-epistemic system				Science as a social system			
1	2	3	4	5	6	7	8
Processes of inquiry	Aims and values	Methods and methodological rules	Scientific knowledge	Professional activities	Scientific ethos	Social certification and dissemination of scientific knowledge	Social values

Although we believe that the categories that make up science as a cognitive-epistemic system are pretty exhaustive, we admit the possibility that other categories might perhaps be added or new categories might emerge as science develops. We do not think, however, that categories of science as a social system is exhaustive in any way. Nor do we claim that this is the only or the best way of describing science as a social system. Others may carve it out differently. Nevertheless, we do believe that it captures an important part of science as social practice. Similarly, we do not pretend to have listed all the items that fall under each of the eight categories above. In fact, we consider them open-ended; that is, the characteristics of science that fall under each category are not fixed and develop historically. Overall, we believe that the eight categories capture the structural features of NOS in a systematic and comprehensive way.

30.4 Clarifying the Meaning of 'Nature of Science' and the Idea of Family Resemblance

Although we suggested that the above eight categories characterise nature *of science*, we have not explored the meaning of term 'nature' that occurs in that phrase. What do we mean by '*nature* of science'? To our knowledge, this is a question that is hardly raised in the science education literature. Here we briefly mention three conceptions of what such a nature might be.

First, the *nature* of science could be taken to be the specification of a natural kind of thing which has an essence, where an essence is a set of properties which a thing *must* have and without which it is *not possible* for that thing exist and to be that *kind* of thing. Triangles have an essence in this sense, but it is very doubtful that science has an essence of this sort. We can agree with Rorty's negative answer to the title of his paper 'Is natural science a natural kind?' (Rorty 1991, pp. 46–62).

A second suggestion about 'nature' is to claim that it is a (small) set of necessary and sufficient properties that something should possess if it is to be deemed science. Here strong modal claims found in the essentialist approach mentioned above are downplayed or eschewed in favour of the mere possession of the set of features shared by all sciences and only by them. However, so far all attempts to define science in terms of necessary and sufficient conditions have failed. Some have restricted their approach to the nature of science by focusing narrowly on just the fourth category of science, viz. scientific knowledge, and then have attempted to define what is to count as science as what is verifiable (some positivists) or what is falsifiable (Popper) and so on.[9] This is not the approach we advocate here in characterising science.

A third approach might be simply to list a number of items falling under the concept of science without pretending to give a set of necessary and sufficient properties or to specify essence for science. Thus one common approach to the *nature* of science in science education lists some salient features of science as in Sect. 30.2. This is also the approach we have adopted by setting out the eight categories of science and listing the items that fall under each. However, there is a problem to be tackled: not all sciences share these features or items all at once. Indeed, a number of science education theorists have drawn attention to important differences amongst scientific disciplines (Samarapungavan et al. 2006; Wong and Hodson 2009). If some sciences lack some of the features others share, what justifies the label 'science' for them? Merely providing a list of preferred items is powerless to answer this question.

Luckily, there is a satisfactory answer within philosophy that invites one to have a quite different approach to what counts as a 'nature' in talk of 'NOS'. In fact it takes us well away from the three ways of understanding 'nature' listed above in using the important idea of family resemblance (Eflin and others 1999; Hacking 1996; Dupre 1993). In a nutshell, the nature of science consists of a set of family resemblances amongst the items that fall under the eight categories of science. In an earlier article, we articulated this approach in some detail for the purposes of science education (Irzik and Nola 2011). In this chapter, we develop it further.

The idea of family resemblance was developed by the philosopher Ludwig Wittgenstein in recognition of the fact that not all terms can be defined in terms of necessary and sufficient conditions or by specifying essences or natures (Wittgenstein 1958, Sects. 66–71). To see this, compare 'triangle' with 'game'. The former can be defined explicitly as a closed plane figure with three straight sides. This definition not only gives six characteristics that specify the necessary and sufficient conditions for being a triangle but also determines the 'essence' of being a triangle or the analytic meaning of the term 'triangle'. In this definition, those properties that are shared by all triangles and only by triangles are specified explicitly. By contrast,

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[9] See some of the following who may be, in addition, critical of the idea of the demarcation of science from non-science but whose focus in so doing is just upon the fourth category, viz. what is to count as a scientific statement: (Alters 1997; Hacking 1996; Laudan et al. 1986; Stanley and Brickhouse 2001; Ziman 2000).

Wittgenstein argued, the term ‘game’ cannot be defined in this way. Any attempt to define the term ‘game’ must include games as different as ball games, stick games, card games, children’s games that do not involve balls, sticks or cards (such as tag or hide-and-seek), solo games (hopscotch) and mind games. Unlike the term ‘triangle’, there is no fixed set of necessary and sufficient conditions which determine the meaning of ‘game’ and thus no set of properties that cover all games and at the same time admit nothing which is not a game.[10] Nevertheless, Wittgenstein argued, all games form ‘a family resemblance’, forming a complicated network of similarities, overlapping and criss-crossing. It is these similarities that justify the use of the term ‘game’ to all those diverse activities from baseball to hopscotch.

Consider a set of four characteristics {A, B, C, D}. Then one could imagine four individual items which share any three of these characteristics taken together such as (A&B&C) or (B&C&D) or (A&B&D) or (A&C&D); that is, the various family resemblances are represented as four disjuncts of conjunctions of any three properties chosen from the original set of characteristics. This example of a polythetic model of family resemblances can be generalised as follows. Take any set S of n characteristics; then any individual is a member of the family if and only if it has all of the n characteristics of S, or any (n-1) conjunction of characteristics of S, or any (n-2) conjunction of characteristics of S, or any (n-3) conjunction of characteristics of S and so on. How large n may be and how small (n-x) may be is something that can be left open as befits the idea of a family resemblance which does not wish to impose arbitrary limits and leaves this to a ‘case by case’ investigation. In what follows we will employ this polythetic version of family resemblance (in a slightly modified form) in developing our conception of science.

Consider the following limiting case. Suppose an example like that above but in which there is a fifth characteristic E which is common to all the disjunctions of conjunctions as in the following: (A&B&C&E) or (B&C&D&E) or (A&B&D&E) or (A&C&D&E). Would this be a violation of the kind of family resemblance definition that Wittgenstein intended? Not necessarily. We might say as an example of characteristic E in the case of games that games are at least activities (mental or physical). Nevertheless, being an activity is hardly definitional of games, nor does it specify a criterion of demarcation; there are many activities that are not games, such as working or catching a bus.

We will see in the case of science that there are characteristics common to all sciences, but are such that they cannot be definitional of it. They cannot be used for demarcating science from other human endeavours either. An example would be observing. We cannot think of a scientific discipline which does not involve making or relying on observations at some point. But then not everything that involves observing is a science (such as being observant when crossing a road in heavy traffic). Similarly, we cannot think of a science that does not involve making some

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[10] John Searle has disputed this example, arguing that ‘game’ can be defined as follows: a series of attempts to overcome certain obstacles that have been created for the purpose of overcoming them (Searle 1995, 103). However this dispute is resolved, there might still be other cases where the family resemblance idea gets some traction, as we think it does in the case of the term ‘science’.

kinds of inference at some point; if it did not, it would not get beyond naive data collecting. Nevertheless, as before, inferring, though common to the sciences, is not exclusive to them. Judges in a court or speculators on the stock market make inferences as well, but they are not doing science.

In the light of these points we can say that there are a few core characteristics that all sciences share (collecting data and making inferences, for instance). Nevertheless, even though they are generic, they are not sufficient either to define science or to demarcate it from other human endeavours. It is the other characteristics that accompany observing and inferring that make an important contribution to the family-forming characteristics that characterise scientific disciplines. It is this modified version of polythetic family resemblance that we will employ in what follows.

30.5 The Family Resemblance Approach to Science

There are many items called ‘science’, ranging from archaeology to zoology. (Here we will exclude the special case of mathematics from our discussion because of its non-empirical character.) So what do these many things called ‘science’ have in common? The idea of family resemblance will tell us that this is a wrong question to ask. What we need to do is to investigate the ways in which each of the sciences are similar or dissimilar, thereby building up from scratch polythetic sets of characteristics for each scientific discipline. The science categories we have introduced in Sect. 30.3 will come in handy for this task.

Begin with the items data collecting, making inferences and experimenting that fall under the category ‘processes of inquiry’. Although all disciplines employ the first two and most (such as particle physics and chemistry) are experimental, there are a few disciplines that are not. Astronomy and earthquake science are cases in point since experiments are simply impossible in these fields. We cannot manipulate celestial objects; nor can we carry out experiments in earthquake science by manipulating earthquakes (though there are elaborate techniques for seismic detection which are not strictly experimental in the sense of experimentation as manipulation that we intend). Consider next the category ‘aims and values’ and the item prediction falling under it. Again, most sciences aim to make predictions, especially novel ones, but not all of them succeed. For example, astronomy is very good indeed in predicting planetary positions. In contrast, even though earthquake science does a good job of predicting the approximate locations of earthquakes, it fails badly with respect to predicting the time of their occurrence. Medicine can statistically predict the occurrence of many diseases under certain conditions without being able to tell who will develop them and when.

Let us now explore the similarities and differences amongst various scientific disciplines in terms of the items under the category ‘methods and methodological rules’. Many sciences employ the hypothetico-deductive method, which can be roughly described as drawing out observable consequences of theories and then checking them against observational or experimental data. For example, particle physics and earthquake science use this method, but there does not appear to be any place for randomised double-blind experiments in these disciplines. In contrast, in evidence-based clinical medical science, the hypothetico-deductive method appears not to be of common use, while the methods of randomised double-blind experiments are the ubiquitous gold standard for testing. Similarly, some very important scientific research projects like sequencing the human genome do not involve much hypothesis testing, but rather are data-driven, inductive inquiries where most of the work is done by computer technologies.

Finally, consider the category of scientific knowledge and the items like laws, theories and models that fall under them. The idea of family resemblance applies here as well since not all sciences may have laws. For example, while there are clearly laws in physics, it is a contested issue as to whether there are laws in biology (Rosenberg 2008).

In the above we have mentioned a number of individual sciences and a number of characteristics. As can be seen for any chosen pair of these sciences, one will be similar to the other with respect to some of these characteristics and dissimilar to one another with respect to other characteristics. If we think of these characteristics as candidates for defining science, then no definition in terms of necessary and sufficient conditions would be forthcoming. If we take a family resemblance approach, however, things look very different and promising. To see this more concretely, let us represent data collection, inference making, experimentation, prediction, hypothetico-deductive testing and blinded randomised trials as D, I, E, P, H and T, respectively. Then we can summarise the situation for the disciplines we have considered as follows:

$$\begin{aligned}&\textit{Astronomy} = \{D, I, P, H\}; \textit{Particle physics} = \{D, I, E, P, H\};\\&\textit{Earthquake science} = \{D, I, P', H\}; \textit{Medicine} = \{D, I, P'', E, T\},\\&\textit{where } P' \textit{ and } P'' \textit{ indicate differences in predictive power as indicated}.\end{aligned}$$

Thus, none of the four disciplines has all the six characteristics, though they share a number of them in common. With respect to other characteristics, they partially overlap, like the members of closely related extended family. In short, taken altogether, they form a family resemblance.

Note that in order to convey the core idea that ‘science’ is a family resemblance concept, we have so far considered characteristics of science understood only as a cognitive-epistemic system. Does the idea of family resemblance apply to science as a social-institutional system as well? We believe that it does, at least to some degree. All scientific disciplines have a peer review system and a system of knowledge certification and dissemination. However, not all of them share exactly the same social values or the same elements of the scientific ethos. For example, the norm ‘respect human and animal subjects’ would not apply to disciplines such as physics and chemistry that do not deal with human and animal subjects, but ‘avoid damaging the environment’ certainly would. Similarly, although many sciences serve social utility, there are some fields (such as cosmology and parts of particle physics such as unified field theory) that are not obviously socially useful in any way; they are practised merely to satisfy our curiosity about the workings of nature. In short, the sciences form a polythetic family resemblance set with respect to their social and ethical dimensions as well.

30.6 Virtues of the Family Resemblance Approach

We believe that the family resemblance approach to science has several virtues, both theoretical and pedagogical. Perhaps the most important theoretical virtue of this approach is the systematic and comprehensive way it captures the major structural features of science and thereby accommodates, in a pedagogically useful way, almost all of the findings of NOS research in science education summarised in Sect. 30.2. As we shall illustrate in the next section, both the categories themselves and the items that fall under them do not dangle in the air as discrete entities; rather, they are tightly related to each other in a number of ways, forming an integrated whole. Thus, we can say that

> Science is a cognitive and social system whose investigative activities have a number of aims that it tries to achieve with the help of its methodologies, methodological rules, system of knowledge certification and dissemination in line with its institutional social-ethical norms, and when successful, ultimately produces knowledge and serves society.

This generic description is not meant as a definition of science, but rather as indicating how various aspects of science can be weaved together systematically as a unified enterprise.

By including science as a social institution as part of the family resemblance approach, the social embeddedness of science emphasised in the NOS literature in science education is captured in a novel way. A significant part of what it means to say that science is socially embedded is to say that noncognitive values are operative in science and influence science. No social institution, not even science, exists in a vacuum, so all kinds of social, cultural, historical, political and economic factors may influence it. Just to give an obvious example, funding strongly affects the choice of scientific problems and research agendas. Noncognitive factors of all sorts (gender biases, ideologies, economic considerations, etc.) may influence data description, hypotheses and even evidential relations in certain areas such as primatology and research on sex differences, as noted by feminist scientists and philosophers (Longino 1990). Sometimes these factors may cause scientists to deviate from the ethical norms of science (they may, e.g. fabricate or suppress data) and thus have a distorting effect on scientific conduct. However, not all social factors have a negative impact on science. Indeed, one of the most important functions of the ethos of science and mechanisms like peer review along with open and free critical discussion is precisely to minimise the negative effects on science. The ethos of science and the social system of scientific knowledge production contribute to the reliability of scientific knowledge as much as scientific methods and methodological rules do.

In practice, scientific inquiry is always guided by both cognitive-epistemic and social-institutional 'rules of the game', so to speak. This gives substance to our earlier claim that the distinction between science as a cognitive-epistemic system and science as a social institution is a conceptual one introduced for analytical purposes; but in practice the two are inseparable.

The historical, dynamic and changing nature of science can be accommodated naturally by the family resemblance approach through its open-ended categories that allow for the emergence of new characteristics of science within each category. For example, from a historical perspective we see that many scientific disciplines such as physics, chemistry, electricity and magnetism became mathematical only after the scientific revolution that occurred in the sixteenth and seventeenth centuries. Similarly, the hypothetico-deductive method was first clearly formulated and became established during the same period. New methodological rules like the one that tells the scientist to use blind procedures in conducting experiments on human subjects in life sciences came about only in the twentieth century. So did many ethical norms of science. The family resemblance approach therefore incorporates the dynamic, open-ended nature of science.

A unique virtue of the family resemblance approach is that it does justice to the differences amongst scientific disciplines and yet at the same time explains their unity by emphasising the similarities and partial overlaps amongst them. It is the existence of these 'family ties' that justify the label 'science' that we apply to various disciplines from archaeology to zoology. The unity of science is a unity-within-diversity. Earlier we pointed out that observing and inferring are common to all scientific disciplines even though they are not unique to the sciences. Another particularly important common feature of all scientific disciplines is the naturalism inherent in them—a feature that has not received sufficient attention in the NOS literature. We have touched upon this in discussing the notion of scientific explanation in Sect. 30.3.1 and are now in a position to articulate it more fully.

Science appeals to only natural entities, processes and events; its mode of explanation, aims and values, ethos, methods and methodological rules and the system of knowledge certification contain nothing that is supernatural or occult. Scientific naturalism is not an addendum to science invented by philosophers; rather, it is inherent to science. As Robert Pennock aptly puts it, it is a 'ground rule' of science so basic that it seldom gets mentioned explicitly (Pennock 2011, p. 184). One of the important science reform documents that does draw attention to this aspect of science is the National Science Teachers Association's statement on NOS: 'Science, by definition, is limited to naturalistic methods and explanations and, as such, is precluded from using supernatural elements in the production of scientific knowledge' (quoted from Pennock 2011, p. 197). Scientific naturalism pervades the whole of science from A to Z. As such, it describes a core aspect of science that contributes to its unity.

A final virtue of the family resemblance approach is that it is free of philosophical commitments such as realism, positivism, empiricism and constructivism. One can adopt any one of these, depending on how one wants to spell out each item that falls under each category of the family resemblance approach. For example, while realist educators may wish to emphasise truth as an aim of science with respect to both observable and unobservable entities, those who are sympathetic to constructivism may settle for viability, provided that they inform students of the existence of alternative views on this issue. Thus, they can add content to the family resemblance approach according to their philosophical orientation or else completely avoid discussing these philosophical issues due to the pressure of limited time, the level of the class and so on.

30.7 Teaching the Family Resemblance Approach: Some Suggestions

Teaching NOS from the perspective of family resemblance can begin by introducing the categories of science and then showing how they are related to one another. A natural place to start is processes of inquiry since all students are engaged in them to varying degrees. A host of interesting questions can be pursued in this context. Is observing a passive activity (raised to illustrate the point that data collection is often driven by scientific problems and theories)? How does observation differ from experimentation? What are the different ways in which a given set of data be interpreted? And so on. Next, the teacher can explore the connection between processes of inquiry, aims and hypotheses (or models and theories). This could be motivated very naturally since processes of inquiry are activities and virtually all activities have some aim or other. Some of the questions that can be asked are as follows. What is the point of doing an experiment? How are observational and experimental data related to hypotheses, theories and models? Does this theory explain that set of data? How would an experiment be set up to test some claim? These and similar questions enable the teacher to make several points: data provide evidence for or against hypotheses, theories and models; experiments are conducted to test them; testing can be done (as in the hypothetico-deductive method) by deducing test predictions from them. The aforementioned questions also provide excellent opportunities for the teacher to discuss key scientific notions like ‘testing’, ‘experiment’, ‘theory’, ‘law’ and ‘model’.

Another fruitful question that prompts the exploration of the relationships amongst various science categories is to ask how science achieves its aims. This may lead to the idea of scientific method and methodological rule. In this context, at least three points can be made. First, science does not achieve its various aims haphazardly, but by employing a number of methods and methodological rules. With their help, science produces reliable (though fallible) knowledge. The hypothetico-deductive method, in particular, enables students to see this clearly. Scientific predictions do not always come out right, and when that is the case, it means that scientists have made a mistake somewhere and they must revise some of their claims. In this way, science can eliminate its errors and produce more reliable results.

Second, methods and methodological rules do not dictate to scientists what to do at every step of their inquiry. A discussion of this point may help students appreciate the fact that scientific methods and rules are not mechanical procedures that generate theories (or models) from data. Hence, theory construction always requires much imagination and creativity. To stimulate creativity, students may be invited to come up with different hypotheses that fit or explain the same data.

Third, despite the existence of methods, methodological rules and values functioning as criteria for evaluating rival theories, scientists may sometimes come to reach different conclusions on the basis of the same body of evidence. This may happen when no single theory embodies all the cognitive-epistemic values equally well and when different scientists place different emphasis on them when faced with a choice amongst rival theories. One scientist may give more weight to fruitfulness, say, and another may value simplicity more due to the priority given to aesthetic considerations (in which case there will be disagreement about which theory is the better one). A historical example that comes close to this scenario is the debate scientists had between Aristotelian-Ptolemaic geocentric system and the Copernican heliocentric system during the early stages of the scientific revolution. The teacher may discuss this case as example of *rational disagreement* amongst scientists, a disagreement which in no way implies that they are acting arbitrarily, though they might have subjective (personal) preferences in weighing values. Properly understood, then, being subjective does not mean acting arbitrarily, which is the whole point of Kuhn (1977). In this way, students can see how both personal (subjective) and intersubjective (objective) factors play a role in scientific theory choice.

Once the students grasp the categories ‘processes of inquiry’, ‘aims and values’ and ‘methods and methodological rules’, then the fourth category can be introduced in a straightforward way: scientific knowledge, especially in the form of theories and models, is the end product of successful scientific inquiry pursuing the aims of truth, testability, prediction and the like under the guidance of scientific methods and methodological rules. The teacher can then draw attention to and explain the characteristics of scientific knowledge which have emerged (such as its empirical, objective and subjective nature, its reliability or tentativeness, its dependence on creativity).

As for the teaching of science as a social-institutional system, we foreground two categories: the scientific ethos and the social certification of scientific knowledge. What must be especially emphasised with respect to these categories is their function in scientific knowledge production. Students must understand that ethical norms like intellectual honesty and openness and social mechanisms of peer review and free and critical discussion are as important as processes of inquiry such as experimenting or in using methods, like the hypothetico-deductive method of testing, in producing *reliable* knowledge. This point can be made forcefully by inviting students to think about what happens if scientists were to fabricate data or to accept an idea or a theory without sufficient critical discussion.

30.8 Conclusion

The main point of this chapter is to suggest a new way of understanding the term ‘nature’ as it gets employed in the phrase ‘nature of science’ (NOS). The word ‘science’ is a broad umbrella term which, in the context of science education, cannot be unproblematically captured by proposing accounts of ‘nature’ which are essentialist or by specifying a set of necessary and sufficient conditions for science. Nor can it be captured by drawing up some small list of features. The problem with a list is that it remains arbitrary as to why some features are included on the list and not others; and it remains unclear how, when given such a list, one is to go on to features not mentioned on the list. Our answer is to suggest the family resemblance or cluster account of a definition—an account developed within philosophy to overcome problems with essentialism, necessary and sufficient conditions and lists already mentioned. As such our enterprise is more philosophical and is not directed upon empirical matters such as the kinds of understanding teachers and pupils might have of NOS, or what level matters pertaining to NOS might be discussed in classrooms. Nevertheless, the family resemblance conception of ‘nature’ that we have proposed is not irrelevant to these empirical matters. What it does is ‘free up’ one’s approach to them in what we hope is an illuminating way which a too rigid conception of ‘nature’ might obscure.

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Chapter 31
Appraising Constructivism in Science Education

Peter Slezak

31.1 Part I: Psychological or "Radical" Constructivism

Referring to von Glasersfeld's (1995a) radical theories, Cobb (1994a, p. 4) writes of the "fervor that is currently associated with constructivism" and Ernest (1995, p. xi) has described it as "the most important theoretical perspective to emerge," receiving "widespread international acceptance and approbation." A review of research in mathematics education noted "In the second half of the 1980s public statements urging the introduction of radical constructivist ideas in school mathematics programs also began to assume bandwagon proportions" (Ellerton and Clements 1991, p. 58). And Catherine Twomey Fosnot observed "Most recent reforms advocated by national professional groups are based on constructivism" (Fosnot 1996, p. x). For example, she cites the National Council of Teachers of Mathematics and the National Science Teachers Association. Fosnot's account has been supported by many other researchers:

> As any glance at contemporary educational literature demonstrates, the concept of "constructivism" carries with it enormous appeal. Contemporary literature also reveals that many current educational reform initiatives encourage teaching practices that many people refer to as constructivist (Null 2004, p. 80).

Denis Phillips (1997a, p. 152) has said of this kind of radical or psychological constructivism, "arguably it is the dominant theoretical position in science and mathematics education," and he remarks, "Across the broad fields of educational theory and research, constructivism has become something akin to a secular religion" (Phillips 1995, p. 5). Indeed, Tobin (1991, p. 1) explains the transformative effects of the doctrine which becomes "a referent for thoughts and actions" that "assume a higher value than other beliefs."

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Despite its significant influence among educationalists,[1] radical constructivism has generated severe controversy and polarization (see contributions to Matthews (1998) and Phillips (2000)). Indeed, von Glasersfeld himself has remarked “to introduce epistemological considerations into a discussion of education has always been dynamite” (quoted in Ernest (1995, p. xi)). Critics including Kelly (1997), Suchting (1992), Matthews (1998, 2000, 2012), Nola (1998), Olssen (1996), Small (2003), and Slezak (2010) have argued that the “radical constructivism” of von Glasersfeld has serious, if not fatal, philosophical problems, and further, it can have no benefit for practical pedagogy or teacher education. Indeed, there are well-conducted studies showing that constructivist-type teaching has a deleterious effect on student learning in science and mathematics (Kirschner et al. 2006; Mayer 2004).[2]

31.1.1 Recoiling into Metaphysical Fantasy

von Glasersfeld (1995a) sees the origins of radical constructivism in Kant, Berkeley, and Piaget, among others. However, the range of philosophical issues raised in the constructivist literature includes abstruse questions whose relevance to practical or theoretical problem in education has been questioned. Thus, among the topics discussed include Berkeleyan idealism, Cartesian dualism, Kantian constructivism, Popperian falsifiability, Kuhnian incommensurability, Quinean underdetermination, truth, relativism, instrumentalism, rationalism, and empiricism, inter alia. Gale (1995, p. xii) identifies “Cartesian epistemology” and the “mind–body split” as having educational relevance. He suggests that constructivist approaches “differed from the Cartesian model in viewing knowledge in a nondualistic manner so as to avoid the mind–body split of endogenic (mind-centered) and exogenic (reality-centred) knowledge” (Gale 1995, p. xiii).

Arguably, good educational theory and practice have flourished despite the persistent obduracy of these problems. Indeed, there is a sharp contrast between such esoteric philosophical matters and the practical recommendations taken to follow from them. Thus, drawing the morals of his constructivism, von Glasersfeld says “Rote learning does not lead to understanding” (Cardellini 2006, p. 182). Similarly, he suggests “after a while they [i.e. students] will become interested in why certain things work and others do not; and it is then that teachers can help to foster this interest that leads to understanding” (Cardellini 2006, p. 182). Critics of constructivism note that such insights are familiar to teachers who are ignorant of constructivism or any other philosophy, for that matter (Nola 1998, p. 33).

von Glasersfeld suggests that his conception of constructivism arose “out of a profound dissatisfaction with the theories of knowledge in the tradition of Western philosophy” and he has suggested that adopting his constructivism “could bring

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[1] See Niaz et al. (2003).

[2] See also Gil-Pérez et al. (2002). Nevertheless, the practical question remains controversial with positive evidence also available.

about some rather profound changes in the general practice of education" (Glasersfeld 1989, p. 135). For example, he recommends, "Give up the requirement that knowledge represents an independent world" (Glasersfeld 1995b, p. 6–7). This is, of course, Berkeley's notorious idealism. von Glasersfeld has addressed objections invited by his frequent allusions to Berkeley. He complains "superficial or emotionally distracted readers of the constructivist literature have frequently interpreted this stance as a denial of 'reality'" (von Glasersfeld quoted by Phillips 1995, p. 6).

However, von Glasersfeld himself encourages the attribution of idealism where he misleadingly claims "all the great physicists of the twentieth century … did not consider [… their theories] descriptions of an observer-independent ontological reality" (quoted in Cardellini 2006, p. 181). Evidently endorsing von Glasersfeld's constructivism, John Shotter (1995, p. 41) says "We also take it for granted that it no longer makes sense to talk of our knowledge of an absolute reality – of our knowledge of a world independent of us – because for us there is no 'external world,' as it used to be called." von Glasersfeld (1989, p. 121) writes of a person's "cognitive isolation from reality" and says Berkeley's insight

> … wipes out the major rational grounds for the belief that human knowledge could represent a reality that is independent of human experience (von Glasersfeld 1995a, p. 34).

However, Putnam (1994, p. 446) has warned that we must find a way "to do justice to our sense that knowledge claims are responsible to reality without recoiling into metaphysical fantasy."

von Glasersfeld's worry appears to address what Rorty has called "the philosophical urge," namely, the urge to say that assertions and actions must not only cohere with other assertions and actions but "correspond" to something apart from what people are saying and doing (Rorty 1979, p. 179). By contrast, in the spirit of Putnam's (1994) "second naiveté," Rorty says that a Quinean naturalism questions

> … whether, once we understand … when and why various beliefs have been adopted or discarded, there is something left called 'the relation of knowledge to reality' left over to be understood (Rorty 1979, p. 178).

In the same vein, Quine has written:

> … it is meaningless, I suggest, to inquire into the absolute correctness of a conceptual scheme as a mirror of reality. Our standard for appraising basic changes of conceptual scheme must be, not a realistic standard of correspondence to reality, but a pragmatic standard (Quine 1961b, p. 79).

von Glasersfeld is evidently led into his idealist worries by failing to distinguish questions concerning the warrant for our beliefs from questions of metaphysics about the existence of a mind-independent world (von Glasersfeld 1989, p. 122).

However constructivism is to be understood, it remains that the relevance of these matters to education remains unclear at best. Ruhloff (2001, p. 64) concludes "There are no compelling reasons … to draw a lesson or practical pedagogical instruction from the results of skeptical analysis." Indeed, in the same spirit, Kant himself wrote, "The only thing necessary is not theoretical learning, but the Bildung [education] of human beings, both in regard to their talents and their character."

31.1.2 *Piaget's "Construction of Reality"?*

Although the title of Piaget's (1999) book *The Construction of Reality in the Child* is suggestive of von Glasersfeld's doctrines, Piaget's own text leaves little doubt about the significant difference between these two. Piaget clearly acknowledges a knowable objective world beyond our sense-data. Despite possibly "flirting with idealism," Piaget (1972a, p. 57) says that his epistemological position is "very close to the spirit of Kantianism," both in its constructivism and in its sensitivity to the need to avoid Berkeleyan idealism. Thus, Margaret Boden writes:

> Piaget is aware that as a constructivist he must be careful to avoid idealism – or, to put it another way, that he must answer the sceptic's challenge that perhaps all our so-called 'knowledge' is mind-dependent illusion. He tries to buttress his commonsense realism by appealing to the biological basis of knowledge (Boden 1994, p. 79).

Piaget himself explains clearly that his views are not an idealistic overestimation of the part played by the subject:

> … the organism is not independent of the environment but can only live, act, or think in interaction with it (Piaget 1971, p. 345).

Thus, while von Glasersfeld is at pains on every occasion to emphasize the unknowability of reality and the need to abandon notions of objectivity and truth, Piaget by contrast writes of "The Elaboration of the Universe" and he asks how the world is constructed by means of the instrument of the sensorimotor intelligence. In particular, Piaget speaks of the shift from an egocentric state to one "in which the self is placed … in a stable world conceived as independent of personal activity" (Piaget 1999, p. 395). Piaget explains:

> The universe is built up into an aggregate of permanent objects connected by causal relations that are independent of the subject and are placed in objective space and time …
>
> … step by step with the coordination of his intellectual instruments … [the child] discovers himself in placing himself as an active object among the other active objects in a universe external to himself (Piaget 1999, p. 397).

Elsewhere, Piaget writes:

> The theory of knowledge is therefore essentially a theory of adaptation of thought to reality … (Piaget 1972b, p. 18).

Although invoking Piaget, these are ways of talking that von Glasersfeld has repudiated.

31.1.3 *The Philosophical Urge*

von Glasersfeld sees his version of constructivism as a departure from traditional conceptions. Meyer (2008) notes that von Glasersfeld and followers such as Gergen (1995) view constructivism "as a replacement for a whole field of philosophy." von

Glasersfeld (1995a) explains that radical constructivism is "an unconventional approach to the problem of knowledge and knowing" that

> … starts from the assumption that knowledge, no matter how it is defined, is in the heads of persons, and that the thinking subject has no alternative but to construct what he or she knows on the basis of his or her own experience (Glasersfeld 1995a, p. 1).

However, we might ask: Who has ever doubted that knowledge is in the head? von Glasersfeld appears to have fallen victim to a notorious problem in philosophy concerning the "veil of ideas" that is supposed to intervene between the mind and the world as the direct objects of perception and knowledge. Von Glasersfeld explains:

> One of Vico's basic ideas was that epistemic agents can know nothing but the cognitive structures they themselves have put together. … God alone can know the real world … In contrast, the human knower can know only what the human knower has constructed.
>
> For constructivists, therefore, the word knowledge refers to a commodity that is radically different from the objective representation of an observer-dependent world that the mainstream of the Western philosophical tradition has been looking for. Instead, knowledge refers to conceptual structures …. (von Glasersfeld 1989, p. 123).

It is precisely this idea that we know only our own ideas or "conceptual structures" directly rather than the world that is the source of the traditional puzzle since the seventeenth century. Putnam (1994) provides a succinct diagnosis of this "disastrous idea":

> … our difficulty in seeing how our minds can be in genuine contact with the 'external' world is, in large part, the product of a disastrous idea that has haunted Western philosophy since the seventeenth century, the idea that perception involves an interface between the mind and the 'external' objects we perceive (Putnam 1994).

31.1.4 Epistemology or Pedagogy?

In an interview, von Glasersfeld was asked whether constructivism is to be understood as an epistemology or pedagogy. His answer is most revealing for von Glasersfeld simply restates the formula of Berkeley as if this serves as an answer to the question: "there is no way of checking knowledge against what it was supposed to represent. One can compare knowledge only with other knowledge" (Glasersfeld 1993, p. 24). Other interviewer questions sought to clarify the "differences between constructivism and idealism," but again, von Glasersfeld reiterates that "we can only know what our minds construct" and that "the "real" world remains unknowable" and that "I could be one of Leibniz' monads" (ibid., p. 28). We might reasonably wonder how this insight could help teachers in the classroom.

When pressed on the question concerning "the implications of constructivism for a theory of instruction," von Glasersfeld suggests that there are many. These include the following: "It is … crucial for the teacher to get some idea of where [the students] are," that is, "what concepts they seem to have and how they relate them" (von Glasersfeld 1993, p. 33). This modest recommendation is far from the “rather profound changes” promised. Similarly, von Glasersfeld says:

> … asking students how they arrived at their given answer is a good way of discovering something about their thinking (von Glasersfeld 1993, p. 33).
>
> Whatever a student says in answer to a question (or ‘problem’) is what makes sense to the student at that moment. It has to be taken seriously as such, regardless of how odd or ‘wrong’ it might seem to the teacher. To be told that it is wrong is most discouraging and inhibiting for the student (ibid., p. 33).
>
> If you want to foster students’ motivation to delve further into questions that, at first, are of no particular interest (from the students’ point of view), you will have to create situations where the students have an opportunity to experience the pleasure inherent in solving a problem (ibid., p. 33).

We may assume that such insights are what Tobin (1993, p. ix) has in mind when he refers to constructivism as “a paradigm for the practice of science education.” Tobin has his own contributions to offer:

> A most significant role of the teacher, from a constructivist perspective, is to evaluate student learning. In a study of exemplary teachers, Tobin and Fraser found that these teachers routinely monitored students in three distinctive ways: they scanned the class for signs of imminent off task behavior, closely examined the nature of the engagement of students, and investigated the extent to which students understood what they were learning. If teachers are to mediate the learning process, it is imperative that they develop ways of assessing what students know and how they can represent what they know (Tobin and Tippins 1993, p. 12).

In brief, good teachers make sure students pay attention and understand the lesson. We may wonder how differently a teacher might do things if not operating “from a constructivist perspective.”

31.1.5 From the Metaphysical to the Mundane

von Glasersfeld had promised that constructivism “could bring about some rather profound changes in the general practice of education.” (von Glasersfeld 1989, p. 135). Elsewhere he has suggested that, “taken seriously,” radical constructivism “is a profoundly shocking view” that requires that “some of the key concepts underlying educational practice have to be refashioned.” However, among these “profoundly shocking” recommendations, he suggests the following:

> … students will be more motivated to learn something, if they can see why it would be useful to know it (von Glasersfeld 1995a, p. 177).
>
> Teaching and training are two practices that differ in their methods and, as a consequence, have very different results. … rote learning does not lead to ‘enlightenment’ (ibid., p. 178).
>
> …in order to modify students’ thinking, the teacher needs a model of how the student thinks (ibid., p. 186).
>
> Students should be driven by their own interest (ibid., p. 188).

> …talking about the situation is conducive to reflection (ibid., p. 188).
>
> To engender reflective talk requires an attitude of openness and curiosity on the part of the teacher, a will to 'listen to the student' (ibid., p. 188).

These are all undoubtedly sound, indeed platitudinous, recommendations, though hardly deserving to be regarded as "profoundly shocking." In this regard, the writing of Driver and colleagues (1995) is instructive:

> …learning science involves being initiated into scientific ways of knowing. scientific entities and ideas, which are constructed, validated, and communicated through the cultural institutions of science, are unlikely to be discovered by individuals through their own empirical inquiry; learning science thus involves being initiated into the ideas and practices of the scientific community and making these ideas and practices meaningful at an individual level. The role of the science educator is to mediate scientific knowledge for learners, to help them make personal sense of the ways in which knowledge claims are generated and validated, rather than to organize individual sense-making about the natural world (Driver et al. 1995, p. 6).

Following the model of C.W. Mills' (1959), Slezak (2010) argues that the passage may be reduced without remainder to the following brief claim: "Learning science involves learning science. Individuals cannot rediscover science by themselves. So, the role of teachers is to teach." Such illustrations have been offered by critics to indicate a tendency to recast truisms in pretentious jargon to create the illusion of deep theory. Tobin and Tippins (1993) provide another typical illustration:

> Constructivism suggests that learning is a social process of making sense of experience in terms of what is already known. In that process learners create perturbations that arise from attempts to give meaning to particular experiences through the imaginative use of existing knowledge. The resolution of these perturbations leads to an equilibrium state whereby new knowledge has been constructed to cohere with a particular experience and prior knowledge (Tobin and Tippins 1993, p. 10).

Translation: Students sometimes learn new things. Tobin and Tippins conclude their article with the following remarks:

> … it is our contention that constructivism is an intellectual tool that is useful in many educational contexts. …We do not claim that use of constructivism as a referent is the only way to initiate changes of … a comprehensive and significant scope, but from our experience we can assert that constructivism can assume a dialectical relationship with almost every other referent in a process that culminates in a coherent world view consisting of compatible referents for action (Tobin and Tippins 1993, p. 20).

Translation: Constructivism is consistent with some other theories.

Constructivist terms have ordinary synonyms which reveal the truisms they assert. Instead of merely saying "talking among teachers and students," we can refer to "the discursive practices that support the coconstruction of scientific knowledge by teachers and students" (Driver et al. 1994, p. 9). Instead of saying simply that "teachers explain new ideas," we can say the "teacher's role is characterized as that of mediating between students' personal meanings and culturally established mathematical meanings of wider society" (Cobb 1994b, p. 15). Rather than the truism "teachers and students exchange ideas," we can say that "speaking from the sociocultural perspective, [we] define negotiation as a process of mutual appropriation in which the teacher and students continually coopt or use each others' contribution" (Cobb 1994b, p. 14). Saying that "students learn different things at different times" may be recast as "Rather than successive equilibrations, … learning may be better characterized by parallel constructions relating to specific contexts" (Cobb 1994a, p. 7).[3]

Such translations make an important point that goes beyond mere ridicule. They reveal what has been referred to as the "paradox of pedagogy." In a survey of the psychological literature, Slezak (2007) suggests that theories taken to be important for education are without bearing despite the ritual claims of relevance. As foregoing truisms suggest, teaching and learning are among the natural, intuitive mental skills that humans display through a tacit knowledge rather than explicit theory or doctrine. In the light of centuries of successful teaching, it seems clear that teachers and learners manage effectively without knowing modern theories of psychology, much less epistemology or metaphysics. Teacher and learner are perhaps best conceived on the analogy of speaker and hearer in a conversation. von Glasersfeld himself makes the more modest point:

> … in summary, the best teachers have always known and used all this information, but they have known and used it more or less intuitively and often against the official theory of instruction. Constructivism does not claim to have made earth-shaking inventions in the area of education; it merely claims to provide a solid conceptual basis for some of the things that, until now, inspired teachers had to do without theoretical foundation (von Glasersfeld 1995b, p. 15).

It is noteworthy that the foremost advocate of von Glasersfeld's constructivism, Ken Tobin, has published an article titled "Constructivism in Science Education: Moving On" in which he writes:

> The critical mass of science educators are still making sense of their praxis in terms of constructivism, but in a short time we will be in another theoretical epoch (Tobin 2000, p. 250).

But nevertheless:

> As an axiom, however, constructivism is the ether for an expanding constellation of theories that illuminate my praxis in science education (p. 251).

Who knows what "is the ether" might mean, but hopefully "the critical mass" of those "illuminating their praxis" by the new "constellation of theories" might subject these new theories to more informed philosophical appraisal than has been evident in the embrace of von Glasersfeld's psychological constructivism.

31.2 Part II: Social Constructivism

Phillips (1995, p. 5) distinguishes the sociological form of constructivism from the psychological variety, and he observes, "It is the work of the social constructivists that had drawn the most dramatic attention in recent years; clearly they have touched

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[3] For further examples, see Matthews (2000).

a raw nerve" (1997a, p. 154). Indeed, the sociological variety of constructivism has been described by Laudan (1990a, x) as "the most prominent and pernicious manifestation of anti-intellectualism in our time" and has been at the center of the "science wars." The book *Higher Superstition* (Gross and Levitt 1994) brought the polemics surrounding social constructivism to wide popular attention. Adding to the controversy, a scandal arose surrounding the "Sokal Hoax" (Sokal and Bricmont 1997)—the unwitting publication of an article by the mathematical physicist Alan Sokal, which was deliberately nonsense, written in the postmodern style.

Although not concerned primarily with educational matters, inevitably, social constructivism has dramatic implications for pedagogy (see Slezak 1994a, b, 2000, 2007). As Phillips notes, "There is a lot at stake. For it can be argued that if the more radical of the sociologists of scientific knowledge … are right, then the validity of the traditional philosophic/epistemological enterprise is effectively undermined, and so indeed is the pursuit of science itself" (1997b, p. 86). The doctrines of social constructivism take scientific theories to reflect the social milieu in which they emerge, and therefore, rather than being founded on logic, evidence, and reason, beliefs are taken to be the causal effects of the historically contingent, local context. Accordingly, if knowledge is intrinsically the product of "external" factors rather than "internal" considerations of evidence and reason, then it is an illusion to imagine that education might serve to instill a capacity for critical thought or rational belief. On these views, education becomes indoctrination, pedagogy is propaganda, and ideas are merely conventional conformity to social consensus. There could be no more fundamental challenge to education than the one posed by social constructivism, since it purports to overturn the very conception of knowledge in the Western tradition: The self-advertising grandiosely proclaims, "The foundations of modern thought are at stake here" (Pickering 1992).

Even among the more temperate critiques in the academic literature, the disputes have been unusually acrimonious. For example, Mario Bunge (1991) has described most of the work in the field as "a grotesque cartoon of scientific research." In a similar vein, the philosopher David Stove (1991) has written of these doctrines as a form of lunacy which is "so absurd, that it eludes the force of all argument," a "philosophical folly," and "a stupid and discreditable business" whose authors are "beneath philosophical notice and unlikely to benefit from it." In his scathing remarks, Stove describes such ideas as an illustration of the "fatal affliction" and "corruption of thought" in which people say things which are bizarre and which even they must know to be false.

31.2.1 Ideas or Ideology? Pedagogy or Propaganda?

Laudan's (1990) charge of anti-intellectualism points to the source of concern for educators. Where traditional views see scientific knowledge as involving insight, inspiration, creativity, and aesthetic judgment, sociologists see something more prosaic and utilitarian. Thus, Collins and Pinch (1992), writing specifically on science education in schools, suggest, "It is nice to know the content of science—it helps one to do a lot of things such as repair the car, wire a plug, build a model aeroplane." This conception leaves out the intellectual dimension and the creative role of the mind in providing an understanding of the world. Instead of conceiving science education as fostering understanding and critical thinking, Collins and Pinch (1992, p. 150) recommend that science education should attend to the social negotiation, "myths," and "tricks of frontier science" as "the important thing."

Above all, the relativism inherent in social constructivist theories makes it impossible for teachers to offer the usual intellectual grounds for distinguishing science from nonsense. Since the rational, cognitive virtues of theories are taken to be irrelevant to their status, one cannot complain that some views are false or implausible or otherwise lacking intellectual, explanatory merit. For example, one cannot teach that Soviet Lysenkoism or Hitler's racialism were perversions of scientific truth. Their success in winning consensus must count ipso facto as exemplary scientific achievement according to social constructivist doctrines. Pseudosciences such as parapsychology and astrology are merely unfashionable rather than scientifically wrong.

31.2.2 What Is Social Constructivism?

The sociology of science and its constructivist doctrines emerged with post-Positivist developments in the philosophy of science and as elaboration of themes found in Kuhn's (1962) influential book *The Structure of Scientific Revolutions*.[4] However, as Zammito (2004, p. 181) notes, Kuhn himself emphatically repudiated these ideas as "absurd," as "deconstruction gone mad," and he "willingly enlisted in the 'science wars' on the side of the scientists."

David Bloor's (1976) book *Knowledge and Social Imagery* launched the so-called Edinburgh Strong Program in the sociology of scientific knowledge (SSK). Bloor was heralding a radical enterprise intended to displace traditional philosophy and epistemology. The essential, astonishing stance was the rejection of "the very idea" of science as a distinctive enterprise, effacing any distinction or boundaries between science and other institutions as merely "rhetorical accomplishments." Typically, Woolgar rejects the traditional "core assumption," namely, "The persistent idea that science is something special and distinct from other forms of cultural and social activity" (Woolgar 1988). A further "assumption" to be rejected is the curiously persistent view "that the objects of the natural world are real, objective and enjoy an independent pre-existence" (Woolgar 1988, p. 26). In place of the traditional "misconceptions" about science and the independent preexistence of the world, social constructivism proposed an amalgam of idealism and relativism according to which scientific theories are merely "fictions," the product of social

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[4] The most comprehensive account of post-Positivism and sociology of science is Zammito (2004).

forces, interests, and other contingent, historical aspects of the milieu in which they arise. That is, the very substantive ideas and content of scientific theories are not explanatory or descriptive of the world, but are socially negotiated by some community of discourse and constituted entirely by social consensus. Even scientific discovery is a matter of "interpretative practice," and "genius has no bearing on the pattern of discovery in science."

Sociologists had a ready explanation for the predictable incredulity of philosophers. Bloor's preface to the first edition of his book hints darkly that the inevitable resistance by philosophers to his doctrines will be due not to the implausibility of the ideas but to uncomfortable secrets that philosophers would wish to hide. Bloor asserts that his approach to science from a sociological point of view encounters resistance because "some nerve has been touched." He announces his intention to "despoil academic boundaries" which "contrive to keep some things well hidden" (Bloor 1976, p. ix). In retrospect, this is somewhat ironic in view of Bloor's own deceptive attempt to hide the commitments of his Strong Program (see Slezak 1994c). Despite making substantive changes in the second edition of his book designed to avoid fatal criticisms by Laudan (1981), in his preface, Bloor denies that he had made any alterations (Bloor 1991). Bloor devotes an entire chapter of his landmark book to a kind of psychoanalysis of his opponents by speculating about the "sources of resistance" to the Strong Program which he attributes to hidden, indeed primitive, motives involving the fear of sociology's desacralizing of science and its mysteries.

One might suggest alternative reasons for the resistance to his sociological doctrines, but Bloor sees only repressed impulses concerning the "sacred" and the "profane" leading to "a superstitious desire to avoid treating knowledge naturalistically" (Bloor 1976, p. 73). Bloor imagines that the "threatening" nature of any investigation into science itself has been the cause of a "positive disinclination to examine the nature of knowledge in a candid and scientific way" (Bloor 1976, p. 42). However, this disinclination to examine knowledge and the need to keep it mystified is difficult to reconcile with the fact that every philosopher since Plato has been centrally concerned with the problem of knowledge and its justification.

31.2.3 "Knowledge as Such": Contexts, Contents, and Causes

In his manifesto, Bloor (1976, p. 3) had declared that the central claims of the Strong Program were "beyond dispute," and Barry Barnes (1981, p. 481) begins an article asserting that in the short time since its advent "developments have occurred with breathtaking speed" and "the view that scientific culture is constructed like any other is now well elaborated and exemplified."

This level of self-congratulatory hyperbole prompted critics such as Gieryn (1982, p. 280) to comment upon such "defenses and reaffirmations" as "expressions of hubris" and "exaggerations passing as fact." Gieryn (1982, p. 293) has suggested that the radical findings of the new sociology of science "are 'new' only in a fictionalized reading of antecedent work." In particular, Robert Merton's (1957) chapter on "The Sociology of Knowledge" had specifically enunciated the very central doctrine of the Strong Program. Merton wrote:

> The "Copernican revolution" in this area of inquiry consisted in the hypothesis that not only error or illusion or unauthenticated belief but also the discovery of truth was socially (historically) conditioned…The sociology of knowledge came into being with the signal hypothesis that even truths were to be held socially accountable, were to be related to the historical society in which they emerged (Merton 1957, p. 456).[5]

Since the Logical Positivists have been a particular target of criticism by social constructivists, it is noteworthy that the Positivist Philipp Frank remarked that in judging the philosophy of science, "we must not ignore the extrascientific factors" since "Every satisfactory philosophy of science has to combine logic of science with sociology of science" (Frank 1949 quoted in Perla and Carifio 2009).

Though it had appeared earlier in different guises in Hegel, Marx, and Durkheim, the radical idea at the heart of the Strong Program was to go beyond those sociological studies which stopped short of considering the actual substantive content, the ideas, of scientific theories as an appropriate domain for sociological investigation. Previously, sociological studies paid attention only to such things as institutional politics, citation patterns, and other such peripheral social phenomena surrounding the production of science, but had not ventured to explain the cognitive contents of theories in sociological terms. Since this crucial point has been obscured, its importance for appreciating subsequent developments cannot be overstated. The opening sentence of Bloor's book asks, "Can the sociology of knowledge investigate and explain the very content and nature of scientific knowledge?"—that is, of "knowledge as such, as distinct from the circumstances of production" (Bloor 1976, p. 1).

The failure of previous sociological studies to touch on the contents of scientific belief was portrayed by Bloor as a loss of nerve and a failure to be consistent. Karl Mannheim, among the founders of the sociology of knowledge, is characterized as failing to make the logical extension of his approach from knowledge of society to the knowledge of nature as well. The epistemological pretensions of the Strong Program—its relativist challenge—derive from this thoroughgoing application of the sociological principle which seeks to explain the hitherto exempted knowledge claims. The ambitions of Bloor's program are explicit from the outset, for he complains that previous sociologists, in "a betrayal of their disciplinary standpoint," had failed to "expand and generalize" their claims to all knowledge: "the sociology of knowledge might well have pressed more strongly into the area currently occupied

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[5] The work of Merton and others who had already formulated the ideas of the current sociology of science are largely ignored today, and so, there is some irony in Merton's remarks which acknowledge, "The antecedents of *Wissenssoziologie* only go to support Whitehead's observation that 'Everything of importance has been said before by somebody who did not discover it'" (1957, p. 456).

by philosophers, who have been allowed to take upon themselves the task of defining the nature of knowledge" (Bloor 1976, p. 1).

31.2.4 Causes and Case Studies

The extensive body of case studies repeatedly invoked by sociologists has been taken to establish the thesis that the contents of scientific theories and beliefs have social causes, in contradistinction to psychological ones. The causal claim concerns such things as "connections between the gross social structure of groups and the general form of the cosmologies to which they have subscribed" (Bloor 1976, p. 3). That is, the very cognitive content of the beliefs is claimed to be causally connected with immediate, local aspects of the social milieu. Of this general thesis, Bloor and Shapin (1979) were evidently unable to believe that anyone might question the causal claims of the Strong Program except on the assumption that they must be unfamiliar with the extensive literature of the case studies. However, in a precise parallel with Durkheim and Mauss (1903) to be noted presently, the claims of social determination of beliefs are all the more extraordinary in view of the failure of these case studies to support them. Critics have challenged precisely the bearing of these studies on the causal claims, and so, repeatedly citing the burgeoning literature is to entirely miss the point.

Of course, scientific discoveries have always necessarily arisen in some social milieu or other, but this is merely a truism holding equally for most human activity not thought to have been actually caused in this way by social factors. However, to the extent that social factors are indeed ubiquitous, establishing a causal connection requires more than merely characterizing in detail the social milieu which must have existed. These more stringent demands have not been met anywhere in the voluminous case studies in the SSK literature. Thus, although Shapin has acknowledged that "the task is the refinement and clarification of the ways in which scientific knowledge is to be referred to the various contextual factors and interests which produce it," and that "we need to ascertain the exact nature of the links between accounts of natural reality and the social order," nevertheless, his much-cited case study of phrenology offers only a variety of anthropological approaches leading at best to a postulation of "homologies" between society and theories which may serve as "expressive symbolism" or perhaps function to further social interests in their "context of use."

This falls far short of demonstrating the strong claims of social determination which abound in the rhetoric of programmatic statements and their "social epistemology." Thus, it is a truism to assert, as Shapin does, merely that "Culture [taken to include science] is developed and evaluated in particular historical situations" (Shapin 1979, p. 42). Shapin undertakes to refute the accusations of empirical sterility by a lengthy recounting of the "considerable empirical achievements" of the sociology of scientific knowledge (Shapin 1979, p. 65). But he is simply begging the question with his advice that "one can either debate the possibility of the sociology of scientific knowledge or one can do it" (Shapin 1982, p. 158).

31.2.5 When Is a Cigar Just a Cigar?

The claimed contingent, historical determination of scientific theories by local social context entails that the substantive content of theories would have been different had the milieu been different. We are inevitably led to ask: Would Isaac Newton have enunciated an inverse *cube* law of gravitation had the society been different? The model of such empirical studies was Forman's (1971) much-cited work which attributes the development of quantum physics to the prevailing milieu in Weimar Germany. However, in the same vein, we might inquire: Did Kurt Gödel's Incompleteness Theorem arise from some lacunae in the Viennese social order of 1930? This admittedly facetious example merely invokes the same suggestive metaphorical connections adduced by social constructivist case studies.

There is, at best, a kind of affinity claimed between the social context and the contents of the theory in question. Thus, Shapin cites "homologies between society and nature" and sees theories as "expressive symbolism" which can be exploited to serve social interests. Given the tenuous nature of such "homologies" between theories and the *zeitgeist*, the distinction between parody and serious claims is difficult to discern. Shapin's *recherché* homologies between theory content and social context recall the Freudian interpretation of dreams, which involved a similar decoding of an allegedly symbolic connection. Likewise, sociology pretends to disclose the hidden meaning underlying our scientific theories. We may have imagined that nineteenth-century theories of phrenology were about the brain, but they were really "expressing a social experience" and were about the "differentiation and specialization [in the social order] perceived by the bourgeois groups" (Shapin 1979, p. 57). Gödel's Incompleteness Theorem, too, undoubtedly expresses a collective longing for wholeness and fulfillment among the Viennese intelligentsia. However, in the spirit of Freud's famous remark, one is tempted to ask: When is a cigar just a cigar?

31.2.6 The Social Construction of Social Constructivism

It is instructive to look at an authoritative and sympathetic statement of social constructivism in a book whose coauthors include two of its founders—*Scientific Knowledge: A Sociological Analysis* by Barnes and colleagues (1996). These authors are uniquely well qualified to offer the book to anyone "seeking a text in the sociology of scientific knowledge." However, borrowing earlier words of one of its authors, this sociological enterprise appears to "contrive to keep some things well hidden" (Bloor 1976, p. ix). A study of the index is revealing. Georg Cantor, infinite cardinal numbers, and the continuum hypothesis get several entries whereas social constructivism and the Strong Program get none at all. In view of the Strong Program being proclaimed with great fanfare as the radical new approach revolutionizing the study of science and epistemology, its omission from the index is revealing. The Duhem–Quine thesis, mentioned *en passant* in an obscure footnote, gets no index entry either, though the book is, in fact, an extended essay on the alleged consequences of this philosophical doctrine. Other omissions from the index are equally curious. In view of the decisive, foundational status of the diametrical opposition between the rationalist "teleological" account and that of the Strong Program, it is striking that this issue, too, has disappeared without trace. This rewriting of history makes it impossible to understand both the social constructivist doctrines themselves and the scandal they have generated (see Slezak 1997).

31.2.7 Relativism

Despite characterizing their book as focused on "basic foundations," Barnes and colleagues (1996) explain that it "gives little prominence" to such issues as relativism, inter alia. Indeed, a prefatory mention of relativism is the only one in the book. However, relativism has been the central, distinctive theoretical doctrine of social constructivism and the source of most disputes. Neglecting to discuss it is somewhat like a text on evolution professing to concentrate on basic foundations and yet choosing to ignore natural selection. The authors' reticence about their own central, and previously explicitly embraced, doctrines is a telling feature of their work (see Barnes and Bloor 1982). Relativism is at the heart of social constructivism because the supposed absence from the constraints of independent "reality" is assumed to warrant appeal to a sociological account of theory acceptance. Relativism, then, is the spurious assumption that there can be nothing more to say about the goodness of our theories if one cannot meaningfully compare them to an independent, inaccessible reality.

However, the question of realism has been the subject of a vast philosophical literature, and both sides of these philosophical arguments accept the rational force of evidence and the usual considerations of explanatory virtue such as comprehensiveness, coherence, and simplicity as grounds for rational theory choice. Social constructivists mistakenly conclude that the inaccessibility of "things in themselves" behind the veil of our theories (whatever this might mean) precludes saying anything sensible about their cognitive virtues.

31.2.8 Theory Choice: Underdetermination of Theory by Evidence

One consideration, above all, has been widely taken to warrant the appeal to sociological factors in the explanation of scientific theory choice. This is an argument which attempts to exploit the underdetermination of theory by evidence—the

Quine–Duhem thesis that there can be no direct inference from observational data to any particular theory, since indefinitely many theories are equally compatible with the same empirical evidence (see Laudan 1990b, p. 6). Therefore, other considerations must be invoked to explain the preference of scientists for one theory over others which are equally consistent with the observational or experimental data. However, a non sequitur from this thesis has become one of the foundational tenets of the social constructivist enterprise. Thus, when distilled to its essence, the entire case underlying Bloor's (1976) manifesto is a spurious inference from underdetermination to social construction.

However, underdetermination is completely neutral among the various alternative resources which might be invoked to explain theory choice beyond conformity with the evidence. Clearly, it has to be shown independently why it might be social factors rather than some others (say, astrological or theological) which are the operative ones in determining theory choice. Boorse (1975) has pointed out that the underdetermination of theories by all possible observational evidence does not make them indistinguishable on other criteria such as simplicity, fecundity, coherence, comprehensiveness, and explanatory power. These are, of course, the kinds of rational considerations typically invoked by the rationalist or teleological account of the growth of scientific knowledge.

Part of the problem may have arisen from an excessively literal construal of theory choice which cannot be considered an actual selection among equivalent available alternatives. Historians, above all, should recognize that the problem in science is typically to find even a single theory which is consistent with the observations. Accordingly, what is termed "choice" is more appropriately described as the psychology of scientific invention or discovery—the subject of a burgeoning research literature (see Langley et al. 1987; Tweney et al. 1981; Gorman 1992; Giere 1992; Slezak 1989).

31.2.9 Consensus as Conventional

Social constructivism rests on this idea that alternative "choices" are equally "good," for theories are adopted by convention—a view that opens the way to sociological relativism. Barnes et al. (1996, p. 154) assert, "Conventions could always be otherwise" suggesting that knowledge might have been negotiated differently had the local interpretative milieu been different and, thereby, inviting the facetious question about Newton's inverse cube law. Indeed, undaunted, the authors embrace precisely such a paradoxical idea even in the case of arithmetical laws (Barnes et al. 1996, p. 184). According to their own account, given the underdetermination of theory by evidence, sociologists must be committed to the possibility of a consensus settling on a vast range of possible laws via the contingent "collective accomplishment" of "fact production" by "local cultural traditions." They suggest that the consensus on "2+2=4" is due merely to "pragmatic reasons connected with the organization of collective action" and the fact that "it is probably easier to organize" than a different convention such as "2+2=5."

31.2.10 Revisiting Durkheim and Mauss: Recoiling in Dismay

These central ideas of social constructivism have a notable pedigree. Emile Durkheim and Marcel Mauss (1903) in their work *Primitive Classification* claimed that the cosmologies of groups such as the Zuñi reflected precise features of their social structure. In his paper "Revisiting Durkheim and Mauss," Bloor (1982, p. 267) invokes them in support of "one of the central propositions of the sociology of knowledge"—namely, their view that "the classification of things reproduces the classification of men." Bloor recommends that Durkheim and Mauss should be rehabilitated after having been consigned to the history books since their work is important for "showing not merely how society influences knowledge, but how it is constitutive of it" (Bloor 1982, p. 297).

It is understandable, of course, that Bloor should commend the virtues of Durkheim and Mauss, for they offer essentially the same metaphorical links between concepts and contexts which have been the stock-in-trade of the sociology of science. However, the Strong Program emulates *Primitive Classification* to the extent of exactly reproducing its severe shortcomings. Thus, a rather different picture emerges if one takes Bloor's invitation seriously to revisit Durkheim's work in the edition cited by him—including the introduction by Rodney Needham. Needham makes trenchant criticisms of Durkheim and Mauss, which are identical with those which have subsequently been leveled against Bloor's Strong Program.

Needham draws attention to Durkheim's claim which Bloor characterizes without demurral as a "bold unifying principle" but which Needham describes as an unwarranted, abrupt inference and logical error which flaws the entire work. On the alleged parallelism between primitive societies and their concepts, Needham writes:

> Now society is alleged to be the model on which classification is based, yet in society after society examined no formal correspondence can be shown to exist. Different forms of classification are found with identical types of social organization, and similar forms with different types of society. … There is very little sign of the constant correspondence of symbolic classification with social order which the argument leads one to expect, and which indeed the argument is intended to explain (Durkheim and Mauss 1903, p. xvi).

Needham notes further that with respect to one of their claims, their "evidences on this point lend their argument no support whatever" and on another claim "nowhere in the course of their argument do the authors report the slightest empirical evidence, from any society of any form, which might justify their statement" (1903, p. xxii). Needham suggests "Durkheim and Mauss's entire venture to have been misconceived" (1903, p. xxvi). In view of the more recent airing of identical concerns, the following remarks are worth quoting in full:

> Yet all such particular objections of logic and method fade in significance before two criticisms which apply generally to the entire argument. One is that there is no logical necessity to postulate a causal connection between society and symbolic classification, and in the absence of factual indications to this effect there are no grounds for attempting to do so. … If we allow ourselves to be guided by the facts themselves, i.e. by the correspondences, we have to conclude that there are no empirical grounds for a causal explanation. In no single case is there any compulsion to believe that society is the cause or even the model of the

> classification; and it is only the strength of their preoccupation with cause that leads Durkheim and Mauss to cast their argument and present the facts as though this were the case (1903, pp. xxiv–xxv).

Although not mentioned by Bloor, these remarks take on special significance in light of the fact that identical claims of the Strong Program have been repeatedly asserted and repeatedly challenged. Needham draws attention to the extensive evidence which actually suggests a conclusion exactly the reverse of that which Durkheim and Mauss suppose. "That is, forms of classification and modes of symbolic thought display very many more similarities than do the societies in which they are found" (1903, p. xxvi). Needham's sober judgment is:

> We have to conclude that Durkheim and Mauss's argument is logically fallacious, and that it is methodologically unsound. There are grave reasons, indeed, to deny it any validity whatever (1903, p. xxix).

Bloor's enthusiasm for reviving the thesis of Durkheim and Mauss is difficult to reconcile with Needham's judgment, "It is difficult not to recoil in dismay" from their "unevidenced and unreasoned" explanations for the complexities of social and symbolic classification (1903, p. xxiii).

31.2.11 Impartiality

Robert Merton, like Karl Mannheim, argued that theories judged to be correct and founded on rational considerations are not in need of sociological explanation in the way that false and irrational theories are. In this sense, traditional conceptions relegated sociological accounts to the residue of false and irrational beliefs. Bloor's revival of the Durkheimian view was explicitly rescuing sociology from this ignominious role by asserting the appropriateness of sociological explanations for all of science regardless of evaluative judgments such as truth and falsity, rationality and irrationality, and success or failure. Our own cosmology and science in general, like those of the Zuñi, were to be shown to be in their entirety reflections of the social milieu.

Bloor's complaint is directed at asymmetrical approaches such as Lakatos's "rational reconstruction" of episodes in the history of science which sought to explain correct scientific theories as products of reasoned thought and, therefore, not requiring resort to sociological explanations. Bloor regards this approach as having the effect of rendering science "safe from the indignity of empirical explanation" altogether (Bloor 1976, p. 7), but for Lakatos, only sociology was to be excluded from accounts of successful science since reasons are a species of explanation themselves. Analogously, veridical perception does not need explanation in the same way as misperception or illusion. We do not ordinarily seek explanatory causes in the case of normal veridical perception, not because we assume that there is no scientific explanation, but because we assume it to be of a certain general sort. Thus, we seek the cause of perceptual failure (such as the influence of alcohol or disease). In the same way, we do not seek to explain why the train stays on the tracks but only why it fails to do so. Again, this asymmetry does not mean that we believe there is no cause or no explanation for the train staying on the tracks. However, this is the view which Bloor (1976, p. 7) imputes to rationalist philosophers such as Lakatos. In his *Knowledge and Social Imagery*, Bloor characterized the "autonomy of science" view he is opposing:

> One important set of objections to the sociology of knowledge derives from the conviction that some beliefs do not stand in need of any explanation, or do not stand in need of a causal explanation. This feeling is particularly strong when the beliefs in question are taken to be true, rational, scientific or objective (1976, p. 5).

Elsewhere, Bloor characterizes the "rationalistic" view that he opposes as "the claim that nothing makes people do things that are correct but something does make, or cause, them to go wrong" and that in the case of true beliefs, "causes do not need to be invoked" (1976, p. 6). Bloor intends to make an absolute distinction between the "teleological" or "rationalist" view which inclines its proponents to "reject causality" (1976, p. 10), on the one hand, and "the causal view," that is, the sociological approach of the Strong Program. On Bloor's own account, the viability of the Strong Program rests on the tenability of this diametrical opposition and, in particular, the falsity of the "teleological model." There could be no more crucial issue for the constructivist program.

Laudan (1981, p. 178) has characterized Bloor's acausal attribution to philosophers as an absurd view which cannot plausibly be attributed to any philosopher at all. In particular, the approach of Lakatos does not deny the existence of causes in cases of rationally held beliefs, but only assumes that reasons are themselves a species of cause (see Phillips 1997b, p. 100). However, Bloor (1981) responded to Laudan by denying these quite explicit earlier intentions. Bloor's discomfort was understandable, since the entire edifice of the Strong Program rests on this claimed opposition. Indeed, in the second edition of his classic book, in the crucial section on the "Autonomy of Knowledge" dealing with the problem of causation, we discover judicious changes to the original text whose rationale is clearly to avoid the criticisms made by Laudan (see Slezak 1991a).

These alterations are impossible to reconcile with Bloor's prefatorial assertion that "attacks by critics have not convinced me of the need to give ground on any matter of substance" and, therefore, "I have resisted the temptation to alter the original presentation of the case for the sociology of knowledge" apart from minor spelling and stylistic changes (Bloor 1991, p. ix). Despite their significance and implications for the entire sociological Strong Program, the exposé of these alterations (Slezak 1994c) has received little attention in the subsequent literature. Bloor had declared forthrightly, "There is no doubt that if the teleological model is true then the strong programme [sic] is false. The teleological and causal models, then, represent programmatic alternatives which quite exclude one another" (Bloor 1976, p. 9).

31.2.12 Social Constructivism as Born-Again Behaviorism

If the “rationalist, teleological, autonomy” view is not the acausal, anti-empirical straw man that Bloor ascribed to philosophers, then its merits need to be confronted seriously. This means acknowledging the full weight of considerations from cognitive science. This, in turn, means rejecting the hostility to internal, mental, or psychological accounts of rational belief which was a central plank of the Strong Program and other varieties of social constructivism.

The purported causal connection between ideas and social context is actually a version of stimulus-control theory akin to that of Skinnerian behaviorism, and not surprisingly, in his later work, Bloor (1983) explicitly endorses such notorious theories. In characterizing opposing rationalist or teleological views, and quoting Ludwig Wittgenstein, Bloor (1983, p. 6) refers to explanations which postulate mental states as infected by the “disease” of “psychologism.” Bloor’s frontal assault on the explanatory force of mental states is an intrinsic part of the defense of the alternative sociological approach to explaining science, but this bold stance left his program vulnerable to a case on the other side whose strength he had grievously underestimated. For example, anachronistically, Bloor’s program depends on rejecting the reality of mental states such as images.

However, this position is 30 years and a major scientific revolution too late. Thus, Bloor (1983, p. 191) has dismissed Noam Chomsky’s review of B. F. Skinner’s *Verbal Behavior* with a passing footnote and a reference to it as the “fashionable” and “standard” criticism of behaviorism. But this reveals a failure to comprehend its significance. One might have expected some indication of the weaknesses of the review and why this merely “fashionable” criticism is to be ignored—particularly since Skinner himself never replied to it. In fact, the Chomsky review is generally regarded as having precipitated the downfall of the entire tradition of behaviorism in psychology.

Bloor’s handwaving is rather more misleading than these comments suggest. Chomsky’s ideas foreshadowed in this review became the foundations of the dramatic developments of the so-called Cognitive Revolution (see Gardner 1987). Bloor’s failure to indicate the magnitude and import of these developments is comparable to defending Creationism today by dismissing the *Origin of Species* as merely “fashionable” and failing to let one’s readers know anything of modern biology founded on Darwin’s theory.[6]

31.2.13 Newton’s **Principia** *as Conditioned Response*

Since behaviorism is a doctrine concerning psychology, it is at first sight surprising that it has been recruited to the cause of social constructivism. However, behaviorism serves Bloor as an ally, since it denies the explanatory role of internal mental

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[6] For further discussion, see Papayannakos (2008).

states and is thereby in diametrical opposition to the rationalist or teleological point of view that the Strong Program is also battling. If scientific beliefs are to be construed as the causal effects of an external stimulus, they are precisely analogous to Skinnerian "respondents" or "operants" and, therefore, science is the result of conditioning. In short, the deep insight of social constructivism is that Isaac Newton's *Principia* is to be explained just like a rat's bar-pressing in response to food pellets.

Bloor's recent protest that his views are entirely consistent with cognitive science cannot be taken seriously and can be asserted at all only because Bloor (1991) now pretends that the sociological thesis at stake is merely whether or not there are social aspects to science. This is significantly different from the claim that knowledge is entirely socially constructed and constituted. This new weak and uncontroversial thesis is not the original doctrine he propounded, whose inconsistency with cognitive science was evident from the accompanying assault on rationalism and the postulation of mental states. The truism that there are social dimensions to science would not have generated the opposition and controversy evoked by the Strong Program. Significantly, Bloor's sociological colleagues have reacted differently: their vehement attacks on cognitive science and artificial intelligence have been both telling and more ingenuous. Their strenuous attempts to discredit the claims of cognitive science have given tacit acknowledgment to the threat these pose to the central sociological doctrines (Slezak 1989). Indeed, Collins (1990), among others, has been perfectly explicit on this point, seeing the claims of artificial intelligence as a crucial test case for the sociology of scientific knowledge (Slezak 1991b).

31.2.14 Revolt Against Reason

Social constructivism is essentially the doctrine characterized in an earlier generation by Karl Popper (1966) as the "revolt against reason"—a rejection of certain ideals of truth and rationality which, however difficult to explicate, are nonetheless central to the Western heritage since the Milesian Pre-Socratics. Popper saw the same tendencies in Hegel which he bitterly denounced as "this despicable perversion of everything that is decent." There can be little doubt about the close affinities between Hegel's doctrines and those of social constructivism: Popper (1966, p. 49) observes that for Hegel, "History is our judge. Since History and Providence have brought the existing powers into being, their might must be right." The parallel is seen in their essentially similar answers to Popper's fundamental question, "who is to judge what is, and what is not, objective truth?" He reports Hegel's reply, "The state has, in general…to make up its own mind concerning what is to be considered as objective truth," and adds, "With this reply, freedom of thought, and the claims of science to set its own standards, give way, finally to their opposites" (1966, p. 43).

Hegel's doctrine expressed in terms of the "state" is essentially the idea that political success is ipso facto the criterion of truth. As we will see presently, this idea is resuscitated by Latour and Woolgar, Pinch and Collins, and the entire enterprise of contemporary social constructivism. This is a historical relativism according to which truth is merely political and dependent on the *zeitgeist* or spirit of the age. It is a view which Popper (1966, p. 308) charges with helping to destroy the tradition of respecting the truth, and his discussion of Hegel's "bombastic and mystifying cant" is striking in its aptness to recent sociology of science and is echoed by Gross and Levitt, Laudan and Stove, and among others. Popper warns against the "magic of high-sounding words" and the "power of jargon" to be found in doctrines which are

> … full of logical mistakes and of tricks, presented with pretentious impressiveness. This undermined and eventually lowered the traditional standards of intellectual responsibility and honesty. It also contributed to the rise of totalitarian philosophizing and, even more serious, to the lack of any determined intellectual resistance to it (Popper 1966, p. 395).

31.2.15 Laboratory Life *Under the Microscope*

Perhaps the most obvious cause for such concern is another celebrated, foundational classic of social constructivism, *Laboratory Life* by Latour and Woolgar (1979). This work is self-consciously subversive, rejecting the rules of logic and rationality as a merely "coercive orthodoxy" (Woolgar 1988). It has the avowed goal of deflating the pretensions of science both in its knowledge claims and in its possession of a special method. Among its iconoclastic goals, the book professes to "penetrate the mystique" (Latour and Woolgar 1979, p. 18), dissolve the appearances, and reveal the hidden realities of science-in-the-making at the laboratory workbench. This study purports to give an exposé of the "internal workings of scientific activity" (Latour and Woolgar 1979, p. 17).

Discovering puzzling questions concerning science, Latour and Woolgar conclude that all of science is merely the "construction of fictions" (1979, p. 284). Latour explains the insights emerging from the new discipline:

> Now that field studies of laboratory practice are starting to pour in, we are beginning to have a better picture of what scientists do inside the walls of these strange places called "laboratories." … The result, to summarize it in one sentence, was that nothing extraordinary and nothing "scientific" was happening inside the sacred walls of these temples (Latour 1983, p. 141).
>
> … The moment sociologists walked into laboratories and started checking all these theories about the strength of science, they just disappeared. Nothing special, nothing extraordinary, in fact nothing of any cognitive quality was occurring there (Latour 1983, p. 160).

Needless to say, if warranted, the implications of such insights must be revolutionary, not least for science education. Indeed, the foregoing remarks have been approvingly quoted in a teachers' journal recommending a radical new vision of "the reality of the scientific process" (Gough 1993). Science education is presumably only socialization into power, persuasion, and propaganda. Rather than learning as a cognitive process involving reasoning, logic, and understanding, education involves merely the observance of arbitrary practices and political interest. Although Latour and Woolgar do not explicitly address the questions of most direct interest to educators as such, their characterization of science clearly suggests the appropriate role of the teacher:

> Each text, laboratory, author and discipline strives to establish a world in which its own interpretation is made more likely by virtue of the increasing number of people from whom it extracts compliance (Latour and Woolgar 1986, p. 285).

On this conception, the function of science teacher is extraction of compliance, more like camp commandant than teacher.

31.2.16 Constructing the World

As a façon de parler, the thesis of "constructing facts" permits a sensible reading according to which a theory or description is settled upon and in a certain sense perhaps even "socially negotiated." However, one can also choose to construe such truisms as something more paradoxical—namely, that objects and substances themselves did not have an independent existence and were socially constructed. In like manner, one might say that Copernicus "removed the earth from the center of the universe," but intending this literally would be an attempt at humor or evidence of derangement. Nevertheless, it is just this sort of claim for which the work of Latour and Woolgar has been acclaimed as a defining text in the genre of ethnomethodology of science.

31.2.17 Witchcraft, Oracles, and Magic Among the Academics

On the face of it, the authors' own description of their project in *Laboratory Life* reads like a parody. Upon entering the Salk Institute for a 2-year study, "Professor Latour's knowledge of science was non-existent; his mastery of English was very poor; and he was completely unaware of the existence of the social studies of science" (1986, p. 273). It is from this auspicious beginning that the "revolutionary" insights into science were to emerge.

Of course, these apparent liabilities are portrayed by Latour and Woolgar as a unique advantage, since "he was thus in the classic position of the ethnographer sent to a completely foreign environment" (1986, p. 273). However, the idea that the inability to understand one's human subjects is a positive methodological virtue is surely a bizarre conception. For Latour and Woolgar, however, it is intimately connected with their doctrine of "inscriptions." The meaninglessness of the "traces, spots, points," and other recordings being made by workers in the laboratory is a direct consequence of Latour's admitted scientific illiteracy. Predictably, all these symbols are indiscriminable to an observer who is completely ignorant, and they must, therefore, be placed in the category of unintelligible markings or "inscriptions." Avoiding the possibility of understanding their subjects' behavior is justified on the grounds that just as the anthropologist does not wish to accept the witch doctor's own explanations, so one should remain uncommitted to the scientists' rationalizations too. However, this attitude follows from the simple failure to appreciate the difference between *understanding* the native and *believing* him.

31.2.18 Persuasion by Literary Inscription and Achieving Objects by Modalities

It is from a point of view of ignorance and incomprehension that Latour comes to rely on a "simple grammatical technique" in order to discern the true significance of the papers accumulating in the laboratory in which he was doing the fieldwork. Undeniably, this method has great merit as an alternative to undertaking many years of undergraduate study and postgraduate work as preparation for his fieldwork. On this grammatical basis, then, Latour and Woolgar obtain their insight: "Activity in the laboratory had the effect of transforming statements from one type to another" (1986, p. 81). Specifically, the rationale of the laboratory activities was the linguistic exercise of transforming statements in various ways in order to enhance their "facticity."

Thus, we see how Latour and Woolgar arrive at their celebrated social constructivist conclusions. They maintain that "a laboratory is constantly performing operations on statements," (1986, p. 86) and it is through this process that "a fact has then been constituted" (1987, p. 87) by social negotiation and construction. In short, the laboratory must be understood "as the organization of persuasion through literary inscription" (1986, p. 88). These are the grounds on which we must understand their claims that substances studied in the laboratory "did not exist" prior to operations on statements (1986, p. 110, 121). "An object can be said to exist solely in terms of the difference between two inscriptions" (1986, p. 127).

31.2.19 Poison Oracles and Other Laboratory Experiments

From the meaninglessness of the "inscriptions" and his revelation that "the 'scientificity' of science has disappeared" (Latour 1983, p. 142), Latour is led inexorably to a "naive but nagging question"—namely, "if nothing scientific is happening in laboratories, why are there laboratories to begin with and why, strangely enough, is the society surrounding them paying for these places where nothing special is produced" (Latour 1983, p. 141)? This is undoubtedly a deep mystery if one systematically refuses to understand the meaningfulness of the "inscriptions" on these papers.

On the analogy of the "anthropologist's refusal to bow before the knowledge of a primitive sorcerer" (1986, p. 29), Latour and Woolgar refuse to accept the authority of our best science, saying, "We take the apparent superiority of the members of our laboratory in technical matters to be insignificant, in the sense that we do not regard prior cognition … as a necessary prerequisite for understanding scientists' work" (1986, p. 29). The affectation that Latour was like Evans-Pritchard among the Azande is "anthropological strangeness" in a rather different sense of the term: No anthropologist was ever so strange. Given his method, predictably, Latour finds the activities in the laboratory completely incomprehensible. Undaunted, and unwilling to allow this to become a liability, it becomes, in fact, the deep insight of *Laboratory Life.* The behavior of the scientists not only appears meaningless, it is meaningless. In their conclusion, Latour and Woolgar reveal that "[a] laboratory is constantly performing operations on statements" (1986, p. 86) and the activities of the laboratory consist in manufacturing "traces, spots, and points" with their "inscription devices." The production of papers with meaningless marks is taken to be the main objective of the participants in essentially the same way that the production of manufactured goods is the goal of any industrial process.

31.2.20 "Derridadaism": Readers as Writers of the Text

Concern about the perversity of this work arises from the fact that in the new edition of their book, Latour and Woolgar (1986) tell us that laboratory studies such as their own should, after all, not be understood as providing a closer look at the actual production of science at the workbench, as everyone had thought. This view would be "both arrogant and misleading" (1986, p. 282) and would presume they had some "privileged access to the 'real truth' about science" which emerged from a more detailed observation of the technical practices. Instead, Latour and Woolgar explain that their work "recognizes itself as the construction of fictions about fiction constructions" (1986, p. 282). This is the textualism of Jacques Derrida combined with a much-vaunted "reflexivity." They continue, "all texts are stories. This applies as much to the facts of our scientists as to the fictions 'through which' we display their work." Their own work, then, just like all of science, has no determinate meaning since "[i]t is the reader who writes the text" (1986, p. 273).

Here, we see a notorious deconstructionist affectation which conveniently serves to protect Latour and Woolgar against any conceivable criticism. The contrast with the work of Bloor is interesting: Where Bloor professes to adhere to the usual principles of scientific inquiry, Latour and Woolgar engage in a game David Lehman (1991) has aptly called "Derridadaism." They manage to evade criticism only by adopting deconstructionist double-talk and affecting a posture of nihilistic indifference to the ultimate cogency of their own thesis. In keeping with the principle of reflexivity, they embrace the notion that their own text (like the science they describe) has no "real meaning," being "an illusory, or at least, infinitely renegotiable concept" (Latour and Woolgar 1986, p. 273).

Reflecting on the controversies surrounding their work, Latour and Woolgar observe that defenders and critics alike have been duped into engaging in this futile "spectacle" in which they have debated the presumed intentions of the authors.

This “spectacle” is, of course, just the traditional exercise of scholarly criticism. Latour and Woolgar now reveal that the “real” meaning of a text must be recognized as illusory and indeterminate. Questions of what the authors intended or what is reported to have happened “are now very much up to the reader.”

This Rorschach inkblot view of their own work is undoubtedly correct in one sense, if only because *Laboratory Life* is in many respects completely incoherent and unintelligible. For example, some of the diagrams offered as explanatory schemas are impossible to decipher. Above all, it is sobering to consider how science teaching might be conducted in accordance with this model of scholarship. Perhaps an indication can be seen in the notorious constructivist claim of Sandra Harding (1986) that Isaac Newton’s *Principia* is a “rape manual.”

31.2.21 Balance of Forces

Though the implications of social constructivism are not drawn out by the authors, these are not difficult to discern. Thus, once Latour and Woolgar reject “the intrinsic existence of accurate and fictitious accounts per se,” the only remaining criterion for judgment is judgment itself. They say “the degree of accuracy (or fiction) of an account depends on what is subsequently made of the story, not on the story itself” (1986, p. 284). There are no grounds for judging the merits of any claim besides the “modalizing and demodalizing of statements,” a purely political question of persuasion, propaganda, and power.

Thus, they suggest that the very idea of “plausibility” of any work, including their own, is not a rational, intellectual, or cognitive question, but simply a matter of political redefinition of the field and other such transformations involving shift in the “balance of forces.” In particular, the current implausibility of their own theory is only due to its relative political disadvantages rather than the lack of any intellectual merits. Apart from being a self-serving justification of any nonsense at all, one could hardly find a more open endorsement of the doctrine that “might is right.” The very distinction between education and indoctrination becomes impossible to draw.

31.2.22 Education: Truth as Power

The bearing of these doctrines on educational questions is starkly brought out in Chomsky’s remarks:

> It is the responsibility of intellectuals to speak the truth and to expose lies. This, at least, may seem enough of a truism to pass without comment. Not so, however. For the modern intellectual, it is not at all obvious (Chomsky 1969, p. 257).

Chomsky quotes Martin Heidegger in a pro-Hitler declaration, echoing social constructivist ideas that “truth is the revelation of that which makes a people certain, clear and strong in its action and knowledge.” Chomsky remarks ironically that for

Heidegger, it seems that it is only this kind of "truth" that one has a responsibility to speak, that is, the "truth" which comes from power. In the same vein, we have seen Latour and Woolgar assert that the success of any theory is entirely a matter of not persuasion but politics and power extracting compliance. On this theory, a repressive totalitarian regime must count as a model of scientific success.

31.2.23 Mertonian Norms: The Ethos of Science

On such a theory, it is impossible to distinguish fairness from fraud in science since, after all, both are ways of constructing fiction. In the absence of the usual distinctions, the scientist who fraudulently manufactures his evidence cannot be meaningfully distinguished from the honest researcher whose data are also "constructed," albeit in different ways. The problem arises from the social constructivists' rejection of the famous Mertonian norms of universalism, communism, disinterestedness, and organized skepticism which constitute the "ethos of science" (Merton 1942). Merton described these as institutional imperatives, being "moral as well as technical prescriptions," that is, "that affectively toned complex of values and norms which is held to be binding" on the scientist. As Merton observes, these institutional values are transmitted by precept and example, presumably in the course of the scientist's education. It is difficult to see how someone committed to the social constructivist view can either teach or conduct science according to the usual rules in which truth, honesty, and other intellectual and ethical measures of worth are taken seriously.

31.2.24 Facticity and Maintaining One's Position

In articulating the same political view of scientific claims, social constructivist authors stop short of openly encouraging cheating and other forms of dishonesty in science, but there can be no mistake about what their theory entails. Thus, when examining a dispute concerning the claims of parapsychology or astrology, Pinch and Collins (1984) draw attention to symmetries in the attempts of opponents to maintain their commitments—in one case, to orthodox science and, in the other, to the paranormal. However, from the standpoint of scrupulous sociological "neutrality" or "impartiality" regarding the intellectual merits of the case on each side, there can be no way to discriminate the relative merits of either the arguments or the evidence itself.

In the case study offered by Pinch and Collins, both sides make questionable attempts to protect their favored theory against contrary evidence and, indeed, the scientists appear to have been less than completely forthright about some disconfirming evidence. Pinch and Collins wish to generalize from this to a thesis about science as a whole by construing it as a typical case, that is, as evidence of the way in which public scrutiny removes the mystique of science and exposes its socially constructed, negotiated character. Such exposé serves to "dissolve the facticity of the claims."

Pinch and Collins are unwilling to see such episodes as anything other than the way science always operates—not because all scientists are dishonest, but because the very distinction relies on being able to discriminate fact from fiction. When the scientists finally admit their error and revise their earlier stance in the light of falsifying evidence, they are ridiculed by Pinch and Collins for their grandiose, mythical pretensions and for appearing to adopt "a mantle of almost Olympian magnanimity" (Pinch and Collins, 536). The scientists are reproached for failing to "re-appraise their understanding of scientific method" and to learn about its "active" character, that is, about the way in which "facts, previously established by their presentation in the formal literature [sic], can be deconstructed" (1984, p. 538) by public scrutiny of the informal, behind-the-scene reality of science.

Remarkably, however, Pinch and Collins suggest that the right lesson about science was that "provided they had been prepared to endorse the canonical model in public while operating in a rather different way in private, they could have maintained their position" (1984, p. 539). In other words, if they had been even more dishonest, they would have been right—in the only sense of "right" possible, that is, they would have "maintained their position." The status or "facticity" of a claim is just a matter of how the claim is publicly presented, and the literature can either construct or "dissolve the facticity of the claims" (1984, p. 523). If we drop all this jargon, their point is simply that truth is what you can get away with.

31.2.25 Altering the Grounds of Consensus: Affirmative Action?

In practice, through the feigned suspension of judgment, social constructivism has led to explicit advocacy of discredited or disreputable pseudoscience. Pinch (1993) and Ashmore (1993) go so far as to defend the supposed "merits" of unorthodox and rejected theories on the grounds of equity. Not least, this policy is evidently taken to include the case of fraud since this "is to be seen as an attributed category, something made in a particular context which may become unmade later" (Pinch 1993, p. 368). Ashmore proposes a radical skepticism concerning the exposé of notorious cases of misguided science such as that of Blondlot's N-rays. Amid the usual jargon-laden pseudotechnicality, such an approach amounts to actually promoting the alleged scientific merits or deserts of such discredited cases. Thus, Pinch writes of "making plausible the rejected view" (1993, p. 371) and Ashmore is perfectly explicit: "To put it very starkly, I am looking for justice! … in a rhetorically self-conscious effort to alter the grounds of consensus" (Ashmore 1993, p. 71). Again, the educational implications for the curriculum should hardly need drawing out. The "impartiality" defended by radical social constructivism has come to mean something like affirmative action for bullshit.[7]

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[7] This may be regarded as a technical philosophical term since Frankfurt's (2005) celebrated article. However, my use of the term does not fit Frankfurt's taxonomy.

31.3 Conclusion

The two main varieties of constructivism considered here have different, but dramatic, consequences for science education. The psychological or "radical" constructivism of von Glasersfeld has had a direct and wide influence on educational theory and practice and makes extravagant claims to overturn the entire tradition of Western epistemology and pedagogical theory. However, when examined critically, radical constructivism appears to offer only commonplaces and platitudes.

By contrast, there could be no more fundamental challenge to science education than the one posed by the sociology of scientific knowledge, since social constructivism purports to overthrow conceptions of rationality, truth, and evidence to be replaced by fashion, negotiation, and consensus. On this view, science is a social institution just like any other. According to social constructivism, there can be no difference between true and false, fact and fiction, fair and fraudulent. On this account, the greatest achievements of the creative human intellect are merely accidents of social context. Isaac Newton was just lucky to be in the right place at the right time.

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Chapter 32
Postmodernism and Science Education: An Appraisal

Jim Mackenzie, Ron Good, and James Robert Brown

32.1 Introduction

Though not easy to define, postmodernism has elicited strong reaction, both laudatory and critical. Some see it as liberating us from the tyranny of science, while others see it as a new form of insanity. It has kinship with some feminist and social constructivist approaches to science, though the overlap is limited. This three-part article will attempt to outline and evaluate some of the main ideas.

Postmodernism in different forms has had, inevitably, an impact on education and specifically science education. A number of countries have explicitly stated that their national science curricula are based on postmodern understanding of science and human knowledge claims. Constructivism, which has been a most influential force in science and mathematics education, is one manifestation of the educational reach of postmodernism. A great deal of research and curriculum construction in multicultural education is predicated on postmodernist epistemological assumptions.

This chapter will first document and give a sense of the impact of postmodernism in science education curriculum and research, then delineate and give some evaluation of the rise of postmodernist positions in philosophy and philosophy of science, and finally return to appraise some of the chief postmodernist arguments and claims in science education. The separate contributions by Good, Brown and Mackenzie have been interwoven to some extent to minimise overlap in their discussion. It will

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be readily appreciated in a complex and controversial topic such as this that the authors will stress different features and not be in full agreement on every detail. Their respective contributions are indicated by initials in the text.

32.2 Part One [R.G.]

32.2.1 Postmodernism in Science Education

In November 1992, the US National Research Council published *National Science Education Standards: A Sampler* and on page A-2 was this statement: 'The National Science Education Standards are based on the postmodern [PM] view of the nature of science'.

For our purposes in this chapter, we will use this statement to mark the beginning of the recognition of PM as an underlying force in the US effort to reform science education. As soon as this statement became known to scientists and others familiar with the history and nature of PM, it was opposed and omitted from later versions of the *Standards*. Among the public statements of opposition, there are two that appeared as editorials in professional journals and each is summarised here. The first, entitled 'The Slippery Slopes of Postmodernism', appeared in the May 1993 issue of *The Journal of Research in Science Teaching* and the following two statements (p. 427) are representative of the overall editorial:

> To question the *objectivity* of observation or the *truth* of scientific knowledge, one does not need to travel to the wispy world of postmodernism. Logical positivism and postmodernism are at the extremes of a long continuum of positions taken by scholars of the nature of science. It is not necessary to carry along the unwanted baggage of either logical positivism or postmodernism to place oneself, as did the authors of *Science for All Americans*, in a more *scientifically* defensible position.
>
> Science education research, like the science education standards being developed by the National Research Council, should be well-grounded on defensible assumptions about the nature of science. The postmodernism of Feyerabend, Foucault, and their followers offers very little insight about the nature of biology and chemistry and physics and so on, that can help in the reform of science education.

Following this editorial, an editorial entitled 'Postmodernism' appeared in the July 9, 1993, issue of *Science*, the journal of the American Association for the Advancement of Science (AAAS). *Science* editor Richard Nicholson begins by questioning whether there is a growing anti-science attitude, providing examples of recent criticisms. He then goes on to ask:

> Are these [criticisms] just isolated events or is something more going on? Harvard's Gerald Holton recently addressed this question from the historian's perspective in a Sigma Xi speech. Holton says "the discussion about science and values has been shifting in remarkable ways" and in this he sees a trend. The trend even has a name: The Postmodern Movement. It is decidedly anti-science. Holton acknowledges that today this movement represents "a minority view." However, he goes on to warn, "but a view held in prominent circles, among persons who can indeed influence the direction of a cultural shift.

An early systematic contribution of postmodernist thinking to education was William Doll's book *A Post-Modern Perspective on Curriculum* (Doll 1993). As a curriculum theorist known for his postmodern perspective, Doll reaches into science and mathematics to the uncertainty theory of Heisenberg, the incompleteness proof of Godel, and especially the chaos theory of Prigogine to craft his vision of a postmodern world. In a separate chapter on 'Prigogine and Chaotic Order', Doll uses a variety of examples, from chaotic pendula to chaotic change in gypsy moth populations to entropy interpretations that supposedly show how evolution can achieve 'perfectibility and perfection of humankind' (p. 100) in his attempt to envision a new postmodern world. According to Doll the paradigm he sees emerging from the insights of chaos theory 'requires of us nothing less than a brand new start in the description of nature—a start which will affect our metaphysics as well as our physics, our cosmology as well as our logic' (pp. 90–91).

In his 1993 book *Science and Anti-Science*, Holton discusses the anti-science phenomenon in detail in the last chapter and some of that discussion is used to focus attention on what he calls the single most malignant part: 'the type of pseudo-scientific nonsense that manages to pass itself off as an *alternative science*, *and does so in the service of political ambition*' (p. 147). He goes on to describe the relatively poor level of scientific literacy in the USA and warns of the dangers to democracy of a poorly informed public, especially in the sciences:

> Today there exist a number of different groups which from their various perspectives oppose what they conceive of as the hegemony of science-as-done-today in our culture. These groups do not form a coherent movement, and indeed have little interest in one another; some focus on the epistemological claims of science, others on its effects via technology, others still long for a romanticized pre-modern version of science. But what they do have in common is that each, in its own way, advocates nothing less than the end of science as we know it. That is what makes these disparate assemblages operationally members of a loose consortium. (p. 153)

In science education, Holton's postmodernist *loose consortium* consists of radical constructivism, queerism, variants of multiculturalism, some versions of feminism and more recently 'cultural studies of science education' (CSSE). They all share a family resemblance of postmodern ontology, epistemology, psychology and social theory. The following four claims are representative of the convictions of this consortium and indicate what is being contested in the 'science education wars'.

Claim One:

> We have to learn how to de-privilege science in education and to free our children from the *regime of truth* that prevents them from learning to apply the current cornucopia of simultaneous but different forms of human knowledge with the aim to solve the problems they encounter today and tomorrow (Van Eijck and Roth 2007, p. 944).

This first statement was published in *Science Education,* a well-established, highly regarded professional journal.

Claim Two:

> In the field of science education, the current views of scientific language and scientific literacy are based on an epistemology that begins the [sic] presupposition of the identity of a thing with itself – both the phenomenon of representation (inscription) and the figure of

> the scientist as rational thinker and actor are premised on this identity. However, recent philosophical scholarship generally and the French philosophers of difference particularly – including Gilles Deleuze, Jacques Derrida, Didier Franck, Jean-Luc Nancy, and Paul Ricœur – take a very different perspective on the question of language. This perspective emphasizes the opposite, that is, the non-self-identity of a thing or person with it or him/herself, which is a conception more compatible with our experiential reality. This perspective also allows us to better theorize the learning of science and scientific literacy in the indeterminate manner in which it is actually experienced and observed (Roth et al 2008, p. 153).

Claim Three:

> Even more hidden and therefore more difficult to recover is the epistemological ground that presupposes equality (e.g., of gender) and sameness (identity of, for example, A and A in the equation A=A) rather than recognizing the inherent plural singularity of each human being. …
>
> If, on the other hand, we begin with the ontological assumption of difference that exists in and for itself, that is, with the recognition that A A (e.g., because different ink drops attached to different paper particles at a different moment in time), then all sameness and identity is the result of work that not only sets two things, concepts, or processes equal but also deletes the inherent and unavoidable differences that do in fact exist. This assumption is an insidious part of the phallogocentric epistemology undergirding science as the method of decomposing unitary systems into sets of variables, which never can be more than external, one-sided expressions of a superordinate unit (Roth and Tobin 2007, pp. 99–100).

The second and third statements were published in a book series *New Directions in Mathematics and Science Education*.

Inasmuch as the third claim can be understood, it lays out what is at stake if postmodernism becomes further established in the science education community. The very achievements of Galileo and Newton depend on studying wholes (falling bodies and planetary motion) by dissolving them into parts (horizontal and vertical motions on an inclined plane and the moon-earth-sun orbits as a 3-body that neglected the effects of other planets, not a multi-body problem as it actually was). Without abstraction and idealisation, science goes nowhere, likewise of course for social science. The latter advances and discovers some things by dividing populations into classes and ascertaining average class weights, health, longevity, etc. and then looking for causal factors in a controlled manner. That no one embodies the 'average weight' does not mean that the construct is mythical and of no use in promotion of public health. In most scientific investigations, the whole cannot be grasped in toto, only in parts. The apple remains red, juicy and attractive even if physicists studying its rate of fall ignore all of this and even if economists likewise abstract from these real features and study the apple's exchange value in a given economic context. In none of this is the reality of the whole apple denied.[1]

This should be a basic lesson learned in science classes, not the reverse lesson that the above authors want students to learn, namely, that such method is 'insidious' and 'phallogocentric'. A historically and philosophically literate science teacher can assist students to grasp just how science captures, and does not capture, the real, subjective, lived world—the 'life world' as it is called by phenomenologists.

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[1] On this important topic, see at least Harré (1989), McMullin (1985) and Nowak (1980).

An HPS-illiterate teacher, or science educator, leaves students with the unhappy choice between disowning their own world as a fantasy and rejecting the world of science as a fantasy, with, sadly, many doing the latter. Aldous Huxley, at the end of World War Two, commented on this matter saying:

> The scientific picture of the world is inadequate, for the simple reason that science does not even profess to deal with experience as a whole, but only with certain aspects of it in certain contexts. All of this is quite clearly understood by the more philosophically minded men of science (Huxley 1947, p. 28).

Claim Four:

> This centripetal tendency of science—a hegemonic, homogenizing force—is well described in the 'pasteurization' of France: Louis Pasteur's science works only when stables in the countryside are made to resemble laboratories, where re-presentations of nature come to be the same irrespective of time and space (Latour 1984); these re-presentations constitute, in Bakhtinian terms, a particular form of chronotope (time-space) (van Eijck and Roth 2011, p. 825).

> Novelization therefore models a process of cultural change toward democracy. In fighting 'for the renovation of an antiquated … language,' novelization is in the interest of those who are located 'outside the centralizing and unifying influence of … the ideological norm established by the dominant literary language.' Novelization constitutes a process of continuous 'linguistic stratification and differentiation' (Bakhtin 1981, p. 67) toward heteroglossia, a process that others much later have referred to as the 'multiplication of meaning' that comes about as the same and different means of expression are produced and stratified (Lat. *Stratum*, spread, layer) one on top of the other (e.g., Lemke 1998) (ibid, pp. 831–2).

> We propose abandoning the dominant notion of science curricula as inculcating the canonical scientific discourse of yesteryear, since this notion comes with its maintenance of a unitary language and hence cultural centralization that does not allow for valuing and keeping cultural diversity in science education (ibid, 840).

This article—'Cultural Diversity in Science Education Through "Novelization": Against the Epicization of Science and Cultural Centralization'—was published in the *Journal of Research in Science Teaching* which is considered by many to be the top professional journal of research devoted to science education and is the official journal of the world's largest science education research organisation (NARST).

After repeatedly warning that traditional science and science education are 'epics' that must be changed through 'novelisation' to ensure the future of multiculturalism and democracy, van Ejick and Roth warn against becoming too successful because that will 'institute the epicisation of novelisation'. In their words:

> We conclude this text with a word of caution. If novelization were to be the name of a form of science education that we aim at and eventually achieve, a new canonical form, then we would have done nothing other than institute the epicization of novelization (p. 843).

It is not difficult to see why one might dismiss this 'epic' project, and more generally, the CSSE project represented in the foregoing four claims, with words like 'a stupid and discreditable business', as Stove (1991) did when summarising the SSK project; 'Fashionable nonsense', the phrase used by Sokal and Bricmont in the title of their 1998 book that describes the postmodern agenda in SSK; or simply as pieces of execrable and inexcusably bad writing designed not to communicate but to obfuscate.

The postmodern movement in science education created its academic home in 2006 with publication of the journal *Cultural Studies of Science Education* with Kenneth Tobin and Wolff-Michael Roth as founding editors. Their aspirations for the journal were expressed as:

> In many ways, this new journal departs from the trodden paths in our discipline. CSSE is unique in focusing on the publication of scholarly articles that employ social and cultural perspectives as foundations for research and other scholarly activities in science education and studies of science. The journal encourages empirical and non-empirical research that explores science and science education as forms of culture, enacted in a variety of fields that are formally and informally constituted. ….We anticipate that the forms of dissemination will make visible the non-linearity of doing research and the recursive nature of delineating problems, deploying theoretical frameworks, constructing data, and adopting dynamic approaches to methodology, design, analysis, interpretation, and writing (Tobin and Roth 2006, p. 1).

What 'dynamic approaches' to methodology, design, analysis and interpretation might mean is left unstated, but the passage itself exhibits what a postmodern 'dynamical' approach to writing might be and why it should be avoided. George Orwell long ago warned of what happens in societies and cultures when such obfuscatory writing goes unchecked and becomes normalised (Orwell 1945).

It is difficult to measure the impact of the many CSSE books and articles in professional journals on the actual science curriculum and instruction in our schools; but the professional recognition given to its proponents is significant (see Chap. 39). The wider cultural and philosophical background that gave rise to postmodern enthusiasm in science education will be outlined in the following sections.

32.3 Part Two [J.M.]

32.3.1 What Is Postmodernism?

The term 'postmodern' was imported into discussions of knowledge (from architecture) by Jean-François Lyotard in *The Post Modern Condition* (1979, tr. 1984) and signified, if nothing else, a suspicion of, and scepticism about, grand narratives or universal claims. In practice, this extended to an opposition to rationality, a rejection of the notion of objective truth and an enthusiastic endorsement of localism (see Brown 2001, p. 76). The opposition to rationality took the form of supposing that scientists' behaviour served only their own social interests and discounting any suggestion that it was related to scientific evidence. In taking this position, the investigator is claiming to know what the scientists' interests are and attributing to those interests efficacy as causes. This is exactly the kind of knowledge of the topic under investigation that they denied scientists could have.[2] The rejection of objective truth

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[2] Harry Collins and Steven Yearley argued: 'Natural scientists, working at the bench, should be naïve realists—that is what will get the work done. Sociologists, historians, scientists away from the bench, and the rest of the general public should be social realists. Social realists must experience

recalled the grand tradition of scepticism and its traditional tropes, which goes back to Sextus Empiricus in around the year 200 CE.

> Those who claim for themselves to judge the truth are bound to possess a criterion of truth. This criterion, then, either is without a judge's approval or has been approved. But if it is without approval, whence comes it that it is truth worthy? For no matter of dispute is to be trusted without judging. And, if it has been approved, that which approves it, in turn, either has been approved or has not been approved, and so on *ad infinitum* (Sextus Empiricus, *Adv. Log.* I 340 = 1935, p. 179).

But Lyotard and others formulation was more than usually conceptually muddled. The localism was adopted as a measure to combat totalising theory which was blamed for the wars and violence of the nineteenth and twentieth centuries. 'We have paid a high price for the nostalgia of the whole and the one …', said Lyotard (1983, p. 46), characteristically exaggerating just how consequential the role of those like himself had been. How academic papers in the humanities and social sciences had made any significant contribution to promoting wars and violence was left unexplained.

32.3.2 Thomas Kuhn and the Origins of Social Constructivism

Science is a social construction. It is an account of the world that has been, and is still being, put together by people. Many would regard this as so obvious as to be hardly worth saying. Nevertheless, over the past thirty or forty years, it has become the slogan of some science educators. They clearly think that it is somehow an important thing to say, one which is contrary to accepted ideas. Keith Tobin proclaimed: 'In 1997 I took a bold step in pronouncing that learning involved cultural production' (2010, p. 23). (It is difficult to think of any pronouncement which would have been less bold.) From their slogan the science educators draw a number of substantive conclusions about science education, such as an emphasis on the social aspects of how children learn science, and advise teachers also to concentrate on these aspects of what they do in the classroom. We need to ask how an idea which would hitherto have been regarded as banal could have come to seem so controversial and significant.

The stage for the conventional landscape in philosophy of science in the twenty-first century was set by a conference on July 13, 1965, at the then Bedford College of the University of London organised by Imre Lakatos. This conference was intended to oppose two thinkers. One was Karl Popper, an Austrian educated philosopher of science, whose seminal book *The Logic of Scientific Revolutions*, though published in German in 1934, had only been available in English since 1959. Popper was more widely known in the English-speaking world for his works on political

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the social world in a naïve way, as the day to day foundation of reality (as natural scientists naively experience the natural world). That is the way to understand the relationship between science and the rest of our cultural activities' (Collins and Yearley 1992, p. 308).

philosophy, *The Poverty of Historicism*, published in three parts in the journal *Economica* in 1944–1945 and in book form only in 1957, and *The Open Society and its Enemies*, first edition 1945. The other was Thomas Kuhn, a Harvard historian of science, whose book *The Structure of Scientific Revolutions* was published in 1962. In organising the debate, Lakatos may have hoped that the debate would cast Popper and Kuhn as the opposing poles, allowing his own position to come through the middle as a less extreme compromise, embodying the strengths of each side. Also present was Paul K. Feyerabend, a former student of Popper, a former colleague of Kuhn at the University of California Berkeley and commentator on drafts of Kuhn's book and a correspondent of Lakatos himself.

But what were the two sides? In conventional accounts of philosophy of science today, they are generally represented with Popper as standing for a narrowly conceived prescriptive view of science, modelled on physics, and as rejecting almost everything apart from physics as insufficiently scientific to merit the name and with Kuhn as a radical, open-minded thinker, firmly based on a sound understanding of the history of the sciences and accepting a wide range of disciplines. That, after all, is how things would surely develop, from narrow to broad, from rigid to flexible and from prescriptive to empirical, and that is how those who compose textbooks most easily organise things. The temptation was perhaps exacerbated by the ages of the principals and the climate of the times: Popper was on the verge of retirement and Kuhn was some 20 years younger, and the social and intellectual turmoil of the 60s was beginning.

Nevertheless, this conventional picture has things almost exactly the wrong way round. Popper had indeed studied physics and used it as an example, and he did draw careful lines of demarcation among theories between those he would accept as scientific and those which were not, framed in terms of falsification by observation. He did not, unlike the positivists of the Vienna Circle, reject what was not scientific as meaningless nonsense: mathematics, history and ethics were all important and reputable disciplines, even though they did not count as science by his criterion. His criterion did, however, exclude from among the sciences not only such soft targets as astrology but the psychoanalysis of Freud and the dialectical materialism of the followers of Marx (Marx's own version may have been scientific, but if so it had already been falsified). Popper rejected traditional ideas of science having to have secure foundations. He was very aware of the need for a social structure to enable scientists to compare, test and above all criticise ideas—science for Popper could not be a merely personal or subjective activity.

Kuhn had begun his academic career as a physicist, and one of the motives behind his work was a desire to explain, or at least to characterise, the difference separating the natural sciences like physics, where practitioners largely agree about what is good work and what is not, from history and other areas in the social sciences, where the very criteria for evaluation are contested. Kuhn proposed as the distinguishing mark of a science that a scientific community shared what he called a *paradigm*, by which he meant an exemplar that serves as a model for future research. To be more specific would be risky: Margaret Masterman (1970) enumerated more than twenty different meanings of the term ‘paradigm’ in Kuhn’s 1962 book. In non-sciences such as history or the study of society, there was no paradigm, and therefore no agreement about what constituted acceptable research. In a science governed by a paradigm, research was merely the working out of puzzles within the universe of the paradigm.

Like the positivists of the Vienna Circle, Kuhn required that science have a solid foundation, but whereas they had sought a foundation in eternally true principles of logic, for Kuhn the foundation lay in the historically situated social practices of interpretation and understanding of a professional community. Since these were not eternal, they were subject to change. For Kuhn, this occurred when ‘normal science’ broke down, increasing numbers of puzzles resisted solution, anomalies multiplied and the community began to be eroded by feelings of anxiety and insecurity. Half-formed ideas about how to proceed would be produced and developed and compared with one another. For a Popperian, this was how a science should be at any time; for Kuhn, it was a suspension of science, a reversion to pre-scientific confusion and a crisis. Popper would hope that the crisis might be resolved, if at all, by members of the scientific community becoming rationally convinced by evidence and arguments that at least some of the competing views should be abandoned and perhaps that all but one should be. Kuhn (1962, p. 150) cited the reminiscences of Max Planck, who in his *Autobiography* (1950, pp. 33–4) had said that a new scientific theory succeeds not by convincing its opponents but by the opponents dying and a new generation familiar with the theory growing up. Though he immediately (p. 151) insisted that scientists were sometimes persuaded by arguments and that on occasion a scientific community would change its mind in advance of biological succession of the next generation, Kuhn’s underlying account of the adoption of a new paradigm is by comparison to the phenomenon of religious conversion.

Initially Kuhn’s work was faced with severe criticisms, ranging from positivists and Popperians to more straightforward historians of science, let alone those worried by its ambiguities and inconsistencies. And of course Kuhn has retracted and qualified many of his claims and has regretted writing ‘the purple passages’ (Kuhn 1991/2000; 1993). But over the last twenty years, a new generation has grown up in the relevant disciplines who take Kuhn unproblematically as the paradigm for the study of science, and who are quite unaware of the original, and often still unanswered, criticisms. The uncritical embrace of Kuhn is especially apparent in the science education community (Matthews 2004).

32.3.3 The Possibility of Objective Truth

A major rhetorical weapon of sceptical positions is to sow doubt about the concept of objective truth. Objectivity presupposes the ability to distinguish the significance a remark has from the perspective of the person to whom it is attributed from its significance from the perspective of the one doing the attributing. As Donald Davidson pointed out, this becomes especially clear when a thought is attributed to a non-verbal creature. ‘The dog, we say, knows that its master is home. But does it know that Mr. Smith (who is his master), or that the president of the bank (who is that same master), is at home?’ (1984, p. 163). Brandom elucidates, ‘The dog knows *of* the president of the bank that he is home, he just does not know *that* the president is home. … [O]ne wants to appeal to the belief that his master is home to explain why the dog is so happy, and to its being a belief *of* the president of the bank (whether the dog knows this or not) in order to explain why one result of the dog’s happiness is that he slobbers on the president of the bank’ (1994, p. 710, n. 95). The same claim is specified differently depending on whether we consider its inferential antecedents and consequences in the context of what is admitted by the attributer or by the one to whom the claim is attributed.

It is this notion of objective truth conditions that makes explicit the possibility of mistaken belief, and so of the difference between what is merely held to be true (believed) and what is correctly held to be true. But objectivity is undermined if the objective correctness of a claim is taken to be what is endorsed by a privileged point of view, such as that of ‘we’, or of the community as a whole. That privileging would leave no possibility for the chosen point of view to be itself mistaken. For objectivity to be possible, no point of view can be globally privileged. Objectivity consists in a perspectival form, rather than any possibility of a non-perspectival content. ‘What is shared by all discursive perspectives is *that* there is a difference between what is objectively correct in the way of concept application and what is merely taken to be so, not *what* it is—the structure, not the content’ (Brandom 1994, p. 600).

This structure is symmetrical. Person A distinguishes between what is to be treated as specifying the objective content and what A regards as specifying the attributee B’s subjective attitude. B does so too but the other way round. This symmetry is what prevents any one perspective from being privileged over all others. ‘Sorting out who should be counted as correct, whose claims and applications of concepts should be treated as authoritative, is a messy retail business of assessing the comparative authority of competing evidential and inferential claims’ (p. 601). A lack of understanding of this perspectival structure leads students of scientists’ behaviour to focus only on what is agreed between them and to neglect of what it is that the scientists are agreeing or failing to agree about: to fail to take account of the *objects* of their discussion, its *object-ivity*.

> From the perspective of our students we might ask, ‘Why should there be so much investment in teaching and learning science?’ Maybe then we will be able to address conceptual change more adequately and for clearer and more significant purposes (Reis 2010, p. 239).

Our investment in science education may be opaque from the perspective of a schoolchild, but it is hardly from that of anybody else. Scientific knowledge is spread through our economy, our health system and our agriculture. Without a solid core of scientifically educated technicians, we could not keep our populations safe from diseases, adequately fed and gainfully employed.

32.3.4 Western and Indigenous Science

Nowadays we routinely hear about 'Western science', whereby 'West' is meant Western Europe and those regions elsewhere predominantly settled by descendants of people from Western Europe. The notion of science as being a cultural product of these people rather than others may have had some validity in the nineteenth century, and indeed even into the 1940s.[3] Science as known today can be, and in Western countries usually is, traced back to ideas largely formulated in Western Europe in the seventeenth century (though see Needham et al. 1954–2004), but it has long ago outgrown that locale and many of the ideas of that time have been superseded or incorporated into subsequent developments. To refer to today's science as Western is to overemphasise its origins and mislead in somewhat the same way as one would by describing modern Christianity as a Middle Eastern religion or the potato as a Peruvian vegetable. The terminology 'Western Science' substantially misrepresents the social context in which science has been done over the last 60 years or so.

The need for this term is of course to draw a contrast: One talks about 'Western' science to contrast it with the sciences of indigenous cultures. In this vein, two advocates of indigenous science have recently written:

> In most countries of the world, a culturally specific (Western) form of science has masqueraded as universal, true and irrefutable. With the introduction of the first national Australian curriculum, Western science and its epistemological base have been challenged by formal expectations that Australian Aboriginal and Torres Strait Islander knowledges be included in formal school science programmes (Baynes and Austin 2012, p. 60).[4]

There is a familiar and pointless debate as to whether indigenous cultures can be said to have sciences. Manifestly every human community has some knowledge of the world in which it lives and how things in that world interact—which plants are poisonous, for example—though that knowledge may not be seen by that community as forming a unified system but as being parts of the lore of hunters, of healers and of midwives. So in that sense every society has its own science. Manifestly no pre-industrial society has had the sort of organised knowledge-sector on which economies like Japan, China, India, Brazil and Russia (as well as Europe and North America) rely in the twenty-first century. In that sense no early society had science. But no cultures, including indigenous ones, are static, and people raised in them often adopt ideas and practices from elsewhere. Science has of course adopted and adapted much knowledge from pre-industrial cultures, and continues to do so. Many people with an indigenous background have become scientists.

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[3] The Nobel Prize for Physics was first awarded outside the 'West' so defined in 1930, to ChandrasekharaVenkata Raman of Calcutta University for his discovery that when light traverses a transparent material, some of the light that is deflected changes in wavelength, a phenomenon now called *Raman scattering*.

[4] Baynes and Austin's use of the word *irrefutable* suggests that their understanding of Karl Popper's contributions to philosophy of science is not very deep. Popper famously maintained that the very defining feature of scientific claims is their refutability (see following section). Such disregard if not ignorance of important philosophical and historical matters is characteristic of the PM 'loose consortium' in science education.

Surprisingly, the dogma that science is a cultural product of, and therefore confined to, Western societies is not opened to empirical test. When an attempt is made to do so, the inconvenient conclusion is often that Western and indigenous sciences agree to an extraordinary extent. Ernst Mayr wrote:

> Forty years ago, I lived all alone with a tribe of Papuans in the mountains of New Guinea. These superb woodsmen had 136 names for the 137 species of birds I distinguished (confusing only two nondescript species of warblers). That … Stone Age man recognises the same entities of nature as Western university-trained scientists refutes rather decisively the claim that species are nothing but a product of the human imagination (Mayr 1963, p. 17, quoted Gould 1980, p. 173).

Subsequent investigations have provided further examples of indigenous taxonomies matching those of Western science.[5] One taxonomy which does diverge from the scientific is the taxonomy embodied in vernacular English. For example, the western class ‘panda’ is confused: cladistically, giant pandas are bears, but red pandas are a separate family more closely related to racoons (Flynn et al. 2005, p. 325a; O’Brien et al. 1985; O’Brien 1987). Charles Sibley and John Ahlquist showed that Australian birds evolved from a crow-like ancestor and that their similarity to various European birds whose names they were given (e.g., warblers and robins) is a matter of evolutionary convergence. Jack Pettigrew has argued (1986) that flying foxes are more closely related to primates than to the microbats. If compared to modern cladistics, the English language with its pandas, robins and bats might fare much less well than many indigenous taxonomies.

A very obvious fact about the sociology of different cultures is that some cultural products have wide appeal, and others remain confined to their original homes. The dramas of Shakespeare, for example, seem to work well in other languages and other dramatic traditions, notably those of speakers of German and Russian, whereas the dramas of Racine have had much less success outside their native French habitat. The music of societies from Africa, including those of Africans transported to the Western hemisphere, has wide appeal those of China and Japan seem not to. The students of the social aspects of science, however, have not investigated this aspect of science’s influence.

32.4 Part Three [J.R.B.]

32.4.1 Postmodernism and Philosophy of Science

Let’s begin with something like *the standard view of science*, which we can roughly express like this: *There is a way things are and scientists try to figure it out; they*

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[5] See, for example, Berlin et al. (1974), Boster and D’Andrade (1989), Diamond (1966), Hunn (1976), Majnep and Bulmer (1977). Though contrast, for example, Björnsen Gurung (2003).

have a variety of (fallible) techniques for doing so and thus far have been quite successful. If pressed for details, we might include the following[6]:

1. There is a world in which there are objects, processes and properties which are independent of us and our beliefs about them. Any statement we make about them is true or is false (or at least approximately so). Of course, we may never know which.
2. The *aim* of science is to give true descriptions of reality. Science can have other aims as well (usually associated with technology), but truth is the chief aim of pure science.
3. We have a variety of tools and techniques (observation, logic, statistical inference, etc.) for learning how things are. These methods have developed from earlier methods and very likely will themselves be developed further.
4. Such methods are fallible; they may lead us astray. Nevertheless, science has made remarkable progress so far. It is reasonable to continue to use these methods in the belief that they are the most reliable source of information about nature.
5. There are no alternatives to this. For instance, the Bible does not give us reliable information about human origins; astrology and precognition do not give us reliable information about our futures and so on.
6. The progress of science is tied to these principles. Social factors can and do influence science, but the main course of its development is based on the recognised methods of evaluation.

Postmoderns and social constructivists generally would consider these points delusional. And yet, this cluster of views is what we all more or less start out with and is what most working scientists believe (though the fifth point might be controversial for some). It is, in short, common sense realism. But, as we know only too well, common sense is sometimes wrong. It is seriously challenged by a number of people active in science studies. Even some who would reject any form of postmodernism will reject parts of the standard picture as sketched here. For instance, various antirealists (including instrumentalists, verificationists and pragmatists) would all reject the idea that science aims at truth that exists independently from us. An instrumentalist such as Duhem claims that a scientific theory aims at ‘saving the phenomena’, that is, getting all the observational claims right but is indifferent to the truth of the theory itself. We might not be able to tell whether the earth rotates or is stationary, while everything else goes around it. What matters, instrumentalists claim, is that we correctly predict the angle at which we see Mars at any specified time. When two theories make the same predictions, we choose to adopt one of them on the basis of convenience—truth (which is inaccessible) has nothing to do with it.

Karl Popper, famous for asserting falsifiability as the defining criterion of scientific theory, would also be critical of aspects of the standard picture but for a different reason. He thought the aim of science is indeed truth, but he didn’t think we could have good inductive evidence for the truth of any theory. Instead, the method of science should be conjectures and refutations. We make a guess, then we try to

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[6] This section draws heavily on Brown (2001).

find counterexamples. When we refute our theory, we then make a new conjecture and so the process goes.

Though Duhem and Popper challenge some aspects of the standard picture of science, they do not quarrel with those features that are most central, namely, the idea that reason and observation play a dominant role in theory evaluation. The postmodern challenge is really quite different. The very idea of scientific reason and objectivity is at issue. Consequently, when we talk about the standard picture of science, we will include Duhem and Popper and almost every other major philosopher of science as embracing that picture. Of course, they differ significantly in detail, but they all hold that reason and observation are at least in principle objective and play a dominant role in science. When we talk about the standard view of science, we mean to include most prominent philosophers of science as upholding some version of it. This would include Whewell, Mill, Mach, Poincaré, Pierce, Duhem, Russell, Carnap, Neurath, Popper, Quine, Lakatos, Putnam, van Fraassen and a great many others. Kuhn and Feyerabend might also be included but are somewhat problematic. Interestingly, they are often seen as postmoderns.

With this outline of the standard view of science in mind, we can better understand the challenge posed by postmoderns and other social constructivists. Let's start by asking: Who's involved? Why should we care? What are the main battle lines?

32.4.2 Antecedents to Postmodernism

In some ways the fight is quite old. The much-cited second-century CE views of Sextus Empiricus and his rejection of the possibility of objectivity have been mentioned above. Two and a half thousand years ago, Protagoras championed a kind of relativism when he said 'Man is the measure of all things'. Plato took up the challenge and fought for objective knowledge. The Enlightenment with its emphasis on progress through rationality was no sooner established in the eighteenth century, then early in the nineteenth it faced the Romantic rebellion which stressed feeling over intellect and emotion over rational inference. Much debate in this century has been stimulated by Karl Marx, though sometimes his writings pull in opposite directions. Marx sounds distinctly like a social constructivist when he famously declared: 'The mode of production of material life conditions the general process of social political and intellectual life. It is not the consciousness of men that determines their existence, but their social existence that determines their consciousness' (1859, 20f.). Yet Marx also thought that objective knowledge is possible; the constructive sentiment gives way to a sensible though subtle form of realism:

> With the change of economic foundation the entire immense superstructure is more or less rapidly transformed. In considering such transformations the distinction should always be made between the material transformations of the economic conditions or production which can be determined with the precision of natural science, and the legal, political, religious, aesthetic or philosophic — in short, ideological — forms in which men become conscious of this conflict and fight it out (*ibid.*, 21).

32.4.3 The Strong Programme in Sociology of Knowledge

Current social constructivism has plenty of antecedents, but it is also reasonable to think of it as mainly a product of the recent past (see Chap. 31). In the mid-1970s David Bloor (in Edinburgh) announced the *strong programme* in the sociology of knowledge. Why *strong*? It's in opposition to *weak* sociology of science, any account which focuses on institutions and various other social features of science but takes for granted that the *content* of science has nothing to do with sociology. By contrast, Bloor asserts that the very content of scientific theories is also to be understood in terms of social factors.

This is a point that must be stressed, since a great deal of sociology of science is quite compatible with the epistemology of scientific orthodoxy while at the same time is potentially embarrassing to the orthodox. So-called weak sociology, for example, can ask: Why are there so few women physicists?, Why do they feel they must sacrifice career or children, and can't (unlike their male colleagues) have both? However, weak sociology of science does not ask questions such as: Why do women believe that the trajectory of a cannon ball is a parabola? The answer to such a question is 'the evidence' and it has nothing to do with their sex, nor with any other sociological factor. Bloor's *strong programme* will have none of this hands-off attitude. He, too, will ask the background questions, of course. But as likely as not, he will relate those factors to the very content of the theory at hand. More on his views below.

There are many others who are like-minded. Shortly after Bloor started to make his mark in science studies, Bruno Latour (a French philosopher and anthropologist) adopted the role of an 'anthropologist in the lab'. With Steve Woolgar he wrote up his experiences of an exotic tribe—a team of California biochemists—explaining their behaviour in social, political and economic terms. Meanwhile in France, Michel Foucault was claiming that *knowledge = power*, not in the sense that by having knowledge one has power (a sense made famous by Bacon), but in the very different sense that having political power allows one to say what knowledge is and is not.

32.4.4 The Sociology of Scientific Knowledge (SSK)

David Bloor's now classic book, *Knowledge and Social Imagery* (Bloor 1976/1991), is perhaps the single most important and influential work in the current social constructivist literature. It contains the manifesto of the *Edinburgh School* known as 'the strong programme'. What (to repeat my earlier question) might the *weak* programme be? To elaborate on my former answer, before Bloor and his like-minded colleagues got to work, *traditional* sociology of scientific knowledge focussed on various issues surrounding science, such as institutions (Who funds them? Why did this one flourish and that one collapse?), scientists (What social class do they come from? Why are there so few women?), relations to governments and corporations

(What impact did the cold war have on science funding? How is the biotech industry influencing research?) and choices of research topics (Why did Galileo take an interest in projectile motion?). But traditional sociology of science would *not* try to account for the *content* of any scientific theory. This, according to Bloor, is what makes the traditional approach 'weak'.

Robert Merton and his school is Bloor's target. Merton's sociology of science does not challenge, but rather complements traditional history and philosophy. Merton, for example, would be happy to account for the growth of science in seventeenth-century England by linking it to Puritanism, as he did in his famous study (1970). But not for a moment would he think it appropriate to give a sociological explanation of why Newton's theory of universal gravitation was widely accepted. Merton formulated a rule of thumb that has come to be known as the *A-rationality Principle*: If a rational explanation for a scientific belief is available, that explanation should be accepted; we should only turn to non-rational, sociological or psychological explanations when rational accounts are unavailable.[7] This is part of the *weak* approach that Bloor explicitly opposes. He insists upon a uniform strategy in dealing with science, one that is utterly thoroughgoing and which penetrates into the very content of scientific theories—in short, he wants a *strong* programme.

Bloor's motivation is his naturalism and his attachment to science. The idea of naturalism is also popular among philosophers, especially philosophers of science, who hold a variety of versions. The general principle is this: The natural world is all there is; there are no special methods of investigating things except the fallible methods of empirical science; norms (whether they be the norms of morality or the norms of scientific method) must be explained away or reduced to the concepts and categories of ordinary science; they must be understood in terms of the natural world.

Naturalism has great appeal, and many would cheer him on, if Bloor said: we want to know about the atom? Study it scientifically! Want to know about disease? Study it scientifically! Want to know about religion? Study it scientifically! Want to know about human society? Study it scientifically! We seem to be tripping right along, and now that we're on a roll, why hesitate? It's hard to resist continuing in the same way: Want to know about science? Study it scientifically! That's what Bloor urges, and it's difficult to object. But what's involved in a scientific study of science itself? Bloor's answer is the four tenets of the strong programme. If you want to adhere to a scientific understanding of science, Bloor claims, then these are the main principles with which your account must comply (See Bloor 1991, p. 7).

Causality: A proper account of science would be causal, that is, concerned with the conditions that bring about belief or states of knowledge.

Impartiality: It would be impartial with respect to truth and falsity, rationality or irrationality and success or failure. Both sides of these dichotomies will require explanation.

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[7] (Merton (1968, p. 516); the principle is also embraced and discussed at length by Laudan (1977, p. 202).

Symmetry: It would be symmetrical in its style of explanation. The same types of cause would explain, say, true and false, [rational and irrational] beliefs.

Reflexivity: It would be reflexive. In principle its patterns of explanation would have to be applicable to sociology itself. Like the requirement of symmetry, this is a response to the need to seek for general explanations. It is an obvious requirement of principle; otherwise sociology would be a standing refutation of its own theories.

Two of these principles seem to be perfectly correct—impartiality and reflexivity. The other two either need serious qualification or are simply wrong. Bloor does not say so, but he seems to assume that reason and evidence are not the sort of things that could be a cause. If we take evidence to be a cause, then there is no objection to the first principle. Let's see what's right about impartiality and reflexivity, which we can do without having to reinterpret them.

Since we're in the business of explaining belief, we're interested in all beliefs, not just the true or rational ones, and not just the false or crazy ones. Optical illusions, for example, are an engaging curiosity and it's nice to have explanations for them. But ordinary veridical perception is also worthy of our intellectual interest. Bloor is not alone in saying this, but he does think the point is underappreciated. The reigning story of how I manage to correctly see a cup on the desk in front of me is a wonderful achievement of physics and physiology research. It involves photons coming from the cup and entering my eye, a signal is sent down the visual pathway into the cortex and so on. Events such as these play a role in explaining how I come to believe that there is a cup on the desk. Whether my perception is veridical or illusory, it needs explaining. The true and the false are in this respect on a par. This is Bloor's impartiality principle. And he's perfectly right to espouse it.

Would anyone think explaining both the true/rational and the false/irrational wasn't the proper thing to do? The impartiality principle hardly seems necessary, yet the A-rationality principle (mentioned above) might be thought to be in conflict. That principle called on giving sociological explanations for beliefs *only* when no rational explanation was available. Actually, there is no conflict between the two principles. Every belief requires explanation, but some will get one type of explanation (say, in terms of social factors), while others will get a different type account (say, in terms of evidence and reason). As we will soon see, this conflicts with Bloor's symmetry principle, but not with impartiality. All sides in this debate can cheerfully embrace the impartiality principle.

What about the principle of reflexivity? Bloor's principle is something that readers immediately pounce on. If all belief is merely the product of various social forces (so this argument goes), then the same can be said of the strong programme itself. There can't be any evidence in support of the strong programme, if Bloor is right, because he has argued that there is no such thing as genuine evidence. Bloor may well believe the strong programme but that (by his own lights) is because it serves his interests.

This sort of self-refutation problem plagues all sorts of views. The sceptic says no belief is justified; thus, the sceptic's own scepticism isn't justified, so we can ignore it. Marx says belief reflects class structure; thus, Marx's own theory merely reflects his social position, so we can ignore it. These kinds of quick rebuttals really won't do, though they are a favourite with beginning philosophy students. It might well be that a particular doctrine is basically right, but any formulation of it runs into problems. It might well be that none of our beliefs is in any way justified, even though *saying so* runs into paradox.

The reflexivity of the sociology of knowledge is a small problem, perhaps none at all. Yes, says Bloor, social factors cause all belief, and yes, social factors even cause the belief that social factors cause all belief. There is certainly no logical problem here. If there is any sort of difficulty, it stems from thinking that if we know a belief is caused by social factors, then our faith in that belief is undermined. So, if we know that belief in the strong programme itself is caused by social factors, then that belief is also undermined. Bloor simply denies this. He staunchly holds that we can simultaneously hold a belief *and* hold that the belief is caused by social factors. Perhaps this is implausible (at least for a wide range of cases); but even if Bloor hasn't answered the self-refuting objection, his reflexivity principle certainly defuses it. Tell him that social factors are making him accept the strong programme and he will smile pleasantly back at you.

The symmetry principle may be the most contentious. It demands the same type of explanation for rational and for irrational beliefs. We can explain your health or your illness in physiological terms. We can explain why a bridge is standing or why it collapsed in terms of its structural properties. These are instances of symmetrical explanations. So, in the same vein we should explain rational and irrational beliefs in the same way. This contradicts the A-rationality principle in that it would demand sociological explanations for all beliefs, not just the irrational ones. An opponent of Bloor could turn this around and demand an explanation in terms of reason for all beliefs, rational and irrational. How could this possibly work? By showing that the agent rationally believes that holding the irrational belief will promote her interests. The symmetry principle looks plausible initially, but on close inspection it crumbles.

SSK rests on two strands. One is the philosophical argument (or should that be anti-philosophical argument) presented by Bloor and others. The other strand is the support it gains from the perceived success of several case studies. These are historical examples where some episode is analysed in sociological terms of 'interest' rather than in terms of reason and evidence, the way a traditional intellectual historian would try to understand the same events. A famous study by Paul Forman well illustrates this.

32.4.5 A Social Constructivist Case Study: Quantum Theory in the Weimar Republic

How do we explain the rise of the quantum theory in the mid-1920s? Paul Forman, in his elaborately titled 'Weimar Culture, Causality and Quantum Theory, 1918–1927: Adaptation by German Physicists and Mathematicians to a Hostile Intellectual Environment', offered a sociological explanation: After the Great War, German scientists lost much of their prestige; Spengler had just published his wildly popular *Decline of the*

West and Spenglerism was everywhere. The spirit of the times was decidedly mystical and anti-mechanistic. The scientists of the Weimar Republic, says Forman, created non-causal, non-deterministic quantum mechanics to appeal to the German public's mystical and anti-mechanistic outlook and thereby to regain their high social standing.

By contrast, a more traditional, 'rational' explanation might look something like this: The old quantum theory of Bohr and Sommerfeld was not a coherent set of physical principles; the new theory of Heisenberg, Born, Schrödinger and others (1925–1927) accounted for a wide range of phenomena including the so-called anomalous Zeeman effect which had been the subject of much perplexity; consequently, scientists who worked in this field were won over by the explanatory successes of the new mechanics and completely accepted it for that reason.

Forman will have none of this. Where others see 'rational' factors, he sees social forces. One need only pay attention to the footnotes of sociological literature in the 1970s and later to see the great importance of Forman's work to the newly emerging style of science studies. To use a Kuhnian expression, it was a new paradigm. The general idea, manifest in Forman's account, is that scientists had social interests and their scientific beliefs are shaped by those interests, not by so-called rational factors. Let's examine Forman's case study in a bit more detail, so that we can clearly see the structure of his argument.

The scientists of the Weimar Republic were living in a hostile intellectual environment, according to Forman. World War I was over and Germany had lost. The public was seriously disillusioned with science and technology. The spirit of the times was mystical and antirational. Indeed there was considerable opposition to science which was seen as mechanical, rationalistic and linked to causality and determinism. Into this hostile intellectual climate came Oswald Spengler's *Decline of the West*, which claimed that physics expressed the 'Faustian' nature of current Western culture. According to Spengler, physics had run its course, exhausting all its possibilities. It stood condemned as a force in opposition to 'creativity', 'life' and 'destiny'. Salvation could only come if science returned to its 'spiritual' home.

Several leading Weimar physicists are cited by Forman stressing the importance of 'spiritual values' and acknowledging the 'mystery of things'. He concludes that the concessions were so numerous and extensive that they constituted a 'capitulation to Spenglerism' (1971, p. 55). And so the general 'crisis of culture' was embraced by the scientists themselves: 'The *possibility* of the crisis of the old quantum theory was dependent upon the physicists' own craving for crises, arising from participation in, and adaptation to, the Weimar intellectual milieu' (1971, p. 62).

Perhaps the most striking feature of quantum mechanics is the widely accepted belief that it abandons strict causality; quantum processes have various probabilities of occurring, but they are not invariably determined to do so. (This is one of the features that Einstein so disliked, claiming that God does not play dice.) Did this new theory which surrendered determinism result from the usual evidential considerations? Not at all, says Forman:

> Suddenly deprived by a change in public values of the approbation and prestige which they had enjoyed before and during Wold War I, the German physicists were impelled to alter their ideology and even the content of their science in order to recover a favorable public

> image. In particular, many resolved that one way or another, they must rid themselves of the albatross of causality (1971, p. 109).
>
> …the movement to dispense with causality expressed less a research program than a proposal to sacrifice physics, indeed the scientific enterprise, to the *Zeitgeist* (1971, p. 113).

Forman's celebrated study became a new model for many historians of science. According to this model, we understand events in the history of science, not in terms of the empirical evidence, not in terms of theoretical innovations, not in terms of conceptual breakthroughs but rather in terms of social factors. A group of scientists in Weimar Germany had a social goal—to regain lost prestige. That's why the old quantum theory was rejected and the new quantum mechanics of Heisenberg, Born and others was adopted.

It's difficult to say why social constructivism has flourished to the extent that it has. One of the reasons is the perceived success of historical case studies such as Forman's. But are they really successful? Lots of historians do think so and lots do not. It's not easy to make a decisive case one way or the other. Certainly, explanations by social factors tend to be more interesting than explanations via dry data and arid inductive inferences. One can read about the events, study the experimental data and laboriously work through the calculations that lead up to the revolution in quantum mechanics in, say, Max Jammer's history of the period (Jammer 1966). Of its kind it's a fine work, but it's also hard going. By contrast, Forman's account is a real page turner with its descriptions of the social atmosphere of post-war Germany, Weimar politics and so on. Social history is often more fun—but that, of course, doesn't mean that it's right.

32.4.6 Feminism and Science

Sandra Harding famously introduced a taxonomy of feminist critiques of science:

1. Feminist empiricism
2. Feminist standpoint theory
3. Feminist postmodernism

She saw feminist philosophers of science as falling into one of these categories. Though something of a simplification, the taxonomy has proved quite useful. The first of these views, *feminist empiricism*, holds that the standard methods of science are fine as they are. Sexist science is the result of not living up to the existing canons of good science. (They often add that the same can be said about racist science.) When looking at nineteenth-century accounts of hysteria or Nazi race science, one cannot help but think that these were appallingly bad researchers who violated every principle of good science.

Feminist standpoint theory comes from Hegel and Marx. A slave has a superior understanding to the slave owner, according to Hegel, because he must understand both his own situation and the owner's. Similarly, for Marx, the worker must understand the boss's view as well as his own. A standpoint is not a mere perspective or point of view. It is an accomplishment requiring a struggle to obtain. For that reason it is a superior understanding of how things are. It is not automatic that women will have a feminist standpoint (unlike a woman's perspective), but if they do achieve it, they will have a better understanding than their male counterparts for whom nothing is to be gained by acquiring an understanding of the position of women. Feminist standpoint theory is a challenge to the standard account of science, but it is important to stress that it remains wedded to the ideal of scientific objectivity. It is just that objectivity is more complex and difficult to obtain than previously thought.

Feminist postmodernism (the third of Harding's categories), as an approach to science, was inspired by a number of feminist postmoderns, such as Judith Butler, Julia Kristeva and Luce Irigaray. It is highly sceptical of general principles and objectivity and takes a very dim view of what is here called the standard view of science. The emphasis is on the local with scant regard for any inconsistencies among different 'local narratives'. It thus embraces a form of relativism. Different societies have their own stories, their own local narratives. An all-embracing or 'total narrative' is dismissed out of hand.

When she proposed the taxonomy, Harding allowed that all three were genuine feminist outlooks, but that she seemed to favour postmodernism. More recently she has pulled away into what she calls 'strong objectivity'. It is generally true that while many feminists have considerable sympathy for postmodernism, the vast majority of feminist philosophers of science do not. In terms of Harding's taxonomy, they adhere to some version of feminist empiricism or standpoint theory, though they may not use these labels.

We can illustrate the more objective feminist approaches with the example of Okruhlik (1994). She begins with two assumptions that are commonly, though not universally, accepted by philosophers of science. One is the distinction between discovery (having new ideas) and justification (putting them to the test). We can ignore the process of discovery, the argument often runs, because the justification process will filter out all the crazy and biased aspects that go into having ideas and only the evidentially supported will survive. Her second assumption is that the process of justification, theory evaluation, is comparative. That is, we do not evaluate a theory merely by testing it against nature. Instead, we test it and its rivals against nature and on that basis we can (objectively) rank order them. We cannot really say a theory is good or bad except with respect to a comparison group. When we say a tennis player is good, we mean she can beat most other tennis players. Imagine that only one tennis player existed. We would have no way of saying she is or isn't a good player; we need the comparison group.

The moral Okruhlik draws from this is rather straightforward. If there is some bias systematically built into the comparison group, it will not be filtered out in the process of justification. What is needed to improve the process of evaluation it to enlarge and diversify the set of rival candidate theories. There are nice illustrations of how this has happened.

There is an important and influential class of theories called 'man-the-hunter' that accounts for human evolution. The general claim is that our ancestors developed language and tool use through the practice of hunting. Male developed tools for hunting and the developed language in order to facilitate cooperative hunting. This even accounts for some aspects of our physiology: large incisors gave way in the evolutionary process to molars, which are better for digestion, because tools replaced the need for teeth that rip apart a prey's throat. There were variations on this general idea and the available evidence would tend to support some of these over others. This was science as usual, rational, objective and so on.

With a growing number of women in anthropology, there arose a different approach to this issue. 'Woman-the-gatherer' theories made a different claim about human evolution. The claim was that our female ancestors are chiefly responsible for our evolution. Tools that were thought to be for hunting were reinterpreted as for food preparation. Language was seen as arising out of sociability. And certain types of facts that had been ignored were investigated. For instance, among contemporary hunter-gatherer communities, it turns out that the female gatherers provide 75% of the family caloric intake.

It does not matter which type to theory is right—perhaps neither is. The philosophical moral is that the quality of the set of rival theories to be evaluated has improved greatly. Okruhlik would not say women researchers are free from bias; rather, they have different biases. But now in the process of comparative evaluation, there is some hope that these biases can be neutralised.

As an approach to understanding science, it is indeed a challenge to the standard view. However, it is more of a modification than a rejection. It requires looking at the scientific community and making sure it is appropriately diverse. This is not a brand of social constructivism, but it does take the society in which science is pursued to be of great importance. This is quite different from the standard account which is largely oblivious to society as long as it does not interfere. Feminist philosophers of science who insist on taking these sorts of social factors into account while still upholding scientific objectivity have probably improved the standard account of science considerably, especially as it applies to the social sciences. Their ranks include Anderson, Harding, Kourany, Longino, Nelson, Okruhlik, Wylie and many others.

There are common misconceptions about feminist critics of science. They are often portrayed as anti-objectivity, anti-science and so on. Of course, some are, but one needs to be, careful when passing judgement. Norette Koertge, a prominent philosopher of science and among the first to write on science education (Koertge 1969), maintains that science needs more unorthodox ideas and a greater plurality of approaches. This is a standard Popperian position which does not in itself constitute an argument for a new epistemology of science. She then sounds the alarm against certain feminists, warning that

> If it really could be shown that patriarchal thinking not only played a crucial role in the Scientific Revolution but is also necessary for carrying out scientific inquiry as we now know it, that would constitute the strongest argument for patriarchy that I can think of (Koertge 1981, p. 354).

And she goes on to say

> I continue to believe that science -- even white, upper-class, male-dominated science -- is one of the most important allies of oppressed people (Koertge 1981, p. 354).

She is quite right, but the problem is that many of those she attacks believe the same thing. Most feminist philosophers of science believe that science can be objective. They are trying to find ways to improve its objectivity, not to expose it as a fraud. Similar sentiments are echoed by many feminists, including Susan Haack (2003) and Cassandra Pinnick (2003, 2005, 2008). Pinnick believes that popular, or postmodernist, feminist philosophy of science is not only unsupportable, but it has done an immense disservice to science and the advancement of women in science. She is right to heavily criticise postmodern approaches, but sometimes she assimilates feminist philosophers who champion objectivity with postmoderns who do not. Pinnick writes

> Viewed by a philosopher of science, there is nothing short of a puzzle as to why, at this date, any group of science educators would invoke so patently flawed a philosophical position as 'epistemologies of feminism', in the hope that women in science will then benefit from a revamped theory of learning that is modelled on or guided by its flawed theoretical notions. It is time that science educators are told, bluntly, the conclusion which philosophers of science have reached after two decades or so of careful, and even hopeful, consideration of feminist standpoint theory. The conclusion, in brief, is that feminist standpoint theory is indefensible (Pinnick 2008, p. 1056).

Expressions such as 'feminist epistemology' cover a variety of views. Helen Longino would advocate doing science as a feminist, by which she means investigating nature with a concern of women's issues. There is no conflict with objectivity here. Thus, a feminist anthropologist might ask new questions about the female gatherers, such as how many calories did they contribute to family intake. They discovered that it is about 75%, which came as a shock to those who thought they had overwhelming evidence for understanding our evolutionary past in terms of man-the-hunter. There is not a hint of different facts of different forms of reasoning for men and women. We might acknowledge different biases that go into theory construction, but those biases can (and we hope will) be overwhelmed by evidence in the long run. Acknowledging this is to promote objectivity.

32.4.7 Postmodern Critics of Science

The foregoing has partially characterised postmodernism but more must be said. Postmodernism stands in opposition to the Enlightenment (which is taken to be the core of modernism). Of course, there is no simple characterisation of the Enlightenment any more than there is of postmodernism, but a rough and ready portrayal might go like this: Enlightenment is a general attitude fostered (on the heels of the Scientific Revolution) in the seventeenth and eighteenth centuries; it aims to replace superstition and authority by critical reason. Divine revelation and Holy Scripture give way to secular science; tradition gives way to progress. Enlightenment advance is of two sorts: scientific and moral. Our scientific beliefs are objectively better than before and are continuing to improve, and our moral and social behaviour is also improving and will continue to do so.

There is another aspect to Modernism which is often linked to the Enlightenment but seems to go well beyond. This is the doctrine that there is one true story of how things are. Jean-François Lyotard, one of the most prominent postmodern commentators, speaks of the ‘incredulity about metanarratives’ (1984). Science for him is just a game with arbitrary rules, and truth is nothing more than what a group of speakers say it is. While most Enlightenment figures that postmoderns attack would happily embrace the view that there is one true story (perhaps with qualifications), so would Aristotle and so would the Mediaevals. In attacking so-called grand narratives or metanarratives, postmoderns are attacking much more than Modernism. Roman Catholicism’s fondness for tradition and authority may stand opposed to the Enlightenment, but it certainly disdains relativism and embraces the one-true-story outlook.

Just as critical reason is seen by postmoderns as a delusion, so are all attempts to generalise or universalise. In place of so-called ‘totalising’ accounts of nature, society and history, ‘local’ accounts are offered. *Localism* or *perspectivalism* is the view that only very limited accounts of nature, or society, (or whatever the subject of discourse is), are to be taken as legitimate; grand theories are invariably wrong or oppressive or both. (To repeat what was said above, standpoint theory is not the same as localism, since it claims that some perspectives are objectively better than others.)

Jacques Derrida, another leading postmodern figure, has pronounced that any attempt to say what postmodernism is (or what it is not) will invariably miss the point. Bruno Latour, a source of inspiration for some postmoderns, has declared that we have never been modern, much less postmodern. Such claims put the would-be expositor in a difficult position. Nevertheless, it seems reasonably fair to say that these three ideas are central to postmodernism: one is the *anti-rationality* stance, a second is the *rejection of objective truth* and the third is *localism.* There are other ingredients such as *anti-essentialism*, but they would seem to follow from the initial ideas. In any case, this short list is not meant to be exhaustive.

Postmodern accounts of science are not easily identifiable. Feminist and SSK approaches usually announce themselves as being feminist and sociological, respectively, but postmoderns, who are often playful with language, find telegraphing prose to be plodding. Nevertheless, we can probably say something by way of characterising it, realising that what we say might be contentious.

The principal characteristic of postmodernism is the rejection of modernism. Modernism, or its equivalent, the Enlightenment, holds that we can and do make progress. This progress is due to reason; tradition and authority are impediments that we can overcome. Needless to say, science and technology are central to this outlook. Postmodernism can now be easily characterised as the rejection of all that. This is true for postmodern science and philosophy, but something like it would be true for postmodern art, music, architecture and so on. Modernist aesthetic principles are similarly rejected. Whereas modernist architects would aim for some sort of unity or symmetry in a building, a postmodern work might be composed of very different styles and building materials. While postmodern science is far from postmodern art, there is still a common spirit underlying each.

One of the striking features of postmodernism—admirable or disconcerting, depending on one's outlook—is the cherry picking of parts of science. While there is widespread distain for science as a 'totalising narrative', particular achievements are celebrated. Heisenberg's uncertainty principle, chaos and catastrophe theory are warmly embraced. It's easy to see why, since these theories involve the unpredictable and the uncontrollable. If it seems strange to embrace some parts of science and not others, remember that unity and coherence are modernist values, cheerfully abandoned by postmodernists. Of course, it makes debate rather difficult, since there seems to be no common ground from which to start.

Obviously postmodernism and the social constructivism with which it is associated pose a challenge to standard views of science, the views most commonly embodied in science curriculum and in arguments for the compulsory study of science in schools. The role of social factors in science is increasingly acknowledged and is now admitted to some extent in all quarters. The stronger forms of constructivism and postmodernism, however, have not been accepted by the general academic community of those who do serious research into the nature of science. On the contrary, postmodern and constructivist views have often foundered and many of their early champions have significantly modified their views and now acknowledge that reason and evidence do after all play a significant or even a determining role in the development of science.

32.5 Part Four [R.G.]

32.5.1 Postmodernism Exposed: The Sokal Hoax

The attempt to subject science to postmodernist interrogation received a major setback when New York University physicist Alan Sokal submitted his parody paper titled 'Transgressing the Boundaries: Toward a Transformative Hermeneutics of Quantum Gravity' to the leading postmodern journal *Social Text.* Embarrassingly the manuscript which was full of gibberish and nonsense that anyone with decent high-school science and mathematics should have detected, passed review and was published (Sokal 1996). Seemingly the journal's readers knew no more about science than its reviewers. The gibberish was 'music to the ears' of postmodern critics of science, speeded its publication, and led to dancing in the Cultural Studies corridors, if not streets. The music can be heard in a few quotes from Sokal's original paper (reproduced in *Fashionable Nonsense*):

- Over the past two decades there has been extensive discussion among critical theorists with regard to the characteristics of modernist versus postmodernist culture; and in recent years these dialogues have begun to devote detailed attention to the specific problems posed by the natural sciences. In particular, Madsen and Madsen have recently given a very clear summary of the characteristics of modernist versus postmodernist science. They posit two criteria for a postmodern science: A simple criterion for science to qualify as postmodern is that it be free from any dependence on the concept of objective truth. By this criterion, for example, the complementarity interpretation of quantum physics due to Niels Bohr and the Copenhagen school is seen as postmodernist. (pp. 223–4)

- In Andrew Ross' words, we need a science that will be publicly answerable to progressive interests. From a feminist standpoint, Kelly Oliver makes a similar argument: …in order to be revolutionary, feminist theory cannot claim to describe what exists, or, 'natural facts.' Rather, feminist theories should be political tools, strategies for overcoming oppression in specific concrete situations. The goal, then, of feminist theory, should be to develop 'strategic' theories—not true theories, not false theories, but strategic theories. (p. 235)
- The teaching of science and mathematics must be purged of its authoritarian and elitist characteristics, and the content of these subjects enriched by incorporating the insights of the feminist, queer, multiculturalist, and ecological critiques. (p. 242)
- Finally, the content of any science is profoundly constrained by the language within which its discourses are formulated; and mainstream Western physical science has, since Galileo, been formulated in the language of mathematics. But whose mathematics? The question is a fundamental one, for, as Aronowitz (1988) has observed, neither logic nor mathematics escapes the 'contamination' of the social. And as feminist thinkers have repeatedly pointed out, in the present culture this contamination is overwhelmingly capitalist, patriarchal, and militaristic: mathematics is portrayed as a woman whose nature desires to be the conquered Other. Thus, a liberatory science cannot be complete without a profound revision of the canon of mathematics. (Aronowitz 1996, pp. 244–245)

Sokal used over 200 references in his parody paper as he repeatedly praised leading PM 'thinkers' for showing how to interpret quantum physics, relativity theory and even mathematics in ways that seemed to provide a sound basis for the various PM agendas. After publication Sokal revealed the hoax and lampooned many of the PM and SSK gurus, including Jacques Lacan, Bruno Latour, Stanley Aronowitz, Jacques Derrida, Sandra Harding and Steve Woolgar. Not surprisingly, *Social Text* did not publish Sokal's revelation and explanation (it did not meet the journal's 'intellectual standards').

Fashionable Nonsense (the work was also published with another title: *Intellectual Impostures*) tells the story behind the parody paper, and in the Epilogue explains why PM can be dangerous to our intellectual health. In doing this Sokal and Bricmont suggest seven lessons (pp. 185–189) that can be learned from the hoax:

1. It's a good idea to know what one is talking about. This is especially true of the natural sciences where technical, abstract ideas are involved for understanding at more than a superficial, popular level.
2. Not all that is obscure is necessarily profound. Much of the discourse of cultural studies is laden with obscure jargon.
3. Science is not a 'text'. Postmodernists often use terms like uncertainty, chaos, theory and nonlinearity in ways that mislead nonscientists. Pseudoscience uses technical, scientific terms to fool people into believing their products have a real scientific basis.

4. Don't ape the natural sciences. The social sciences study people and their institutions, while the natural sciences study nature and these domains often require different assumptions and research methods.
5. Be wary of argument from authority. The tendency to follow gurus like Lacan and Freud in the social sciences is much more prevalent than in the natural sciences. Nature is the final authority in the natural sciences, not sacred texts or respect for culture.
6. Specific scepticism should not be confused with radical scepticism. The relativism inherent in postmodernism allows followers to question the value of logic and evidence. Embracing radical scepticism can result in the absurd conclusion that astrology and astronomy are equally valid.
7. Ambiguity as subterfuge. Postmodernists are often ambiguous on purpose as this allows one to claim, I was misunderstood. Deliberate ambiguity in their writing is a common strategy among postmodern authors.

These lessons from the Science Wars and the exposure of the severe intellectual problems surrounding the sociology of science knowledge (SSK) programme should have meant that postmodernism would lose its appeal by the end of the twentieth century. However, that is not the case; postmodernism survives, and as documented in Part One of this chapter, even thrives in some science education circles under the guise of 'cultural studies' or 'radical constructivism'.

32.6 Part Five Conclusion [R.G., J.M. & J.R.B.]

The anti-science attitude fostered by postmodernism and relativism can lead to habits of mind that diminish concern for evidence, for logic, for clear writing and for finding out the truth of the matter. A good example of this is the widespread rejection of the findings of modern climate science. Despite overwhelming evidence that burning fossil fuels results in a warming of Earth's climate, with potentially devastating results for all living things, many people reject the scientific findings. When ideology trumps science, as in climate science debates where oil and coal companies resist scientific findings and related implications for action, we are left with no reasonable way to solve problems. The same pattern is repeated in campaigns against child and adult vaccination. When scientific knowledge is seen as a 'regime of truth' that endangers our freedom and democracy, as suggested by PM proponents, then political and religious ideologies can replace knowledge gained through scientific methods; it becomes much more difficult for people to recognise and reject pseudoscience. Science's most precious gift, the phrase used by Albert Einstein to describe the great value of modern science to society, is its ability to reduce the influence of cultural ideologies in judging the truth value of competing claims. Postmodernism offers little that can be used to improve the scientific literacy of our citizens, little that can be used to improve teacher education and a lot that can be used to diminish literacy and distract good teacher education.

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Chapter 33
Philosophical Dimensions of Social and Ethical Issues in School Science Education: Values in Science and in Science Classrooms

Ana C. Couló

33.1 Values in Science Classrooms?

To date, there is no unanimous consensus on the “fundamental” notions related to the nature of science that should be taught within a history and philosophy of science (HPS) frame. However, the role of values in science has usually been a key element of the list, both in curricular proposals and in science education research (Adúriz-Bravo 2005a; Clough 2007; McComas 2002). Science has a significant impact on the way we live our lives, either through its products and processes or through the impact of new ideas on the ways we think about ourselves and the world. Scientific and technological developments raise many controversial issues: cancer treatment isotopes, increased-yield crops and xenotransplantation which saves human lives, on one side, and nuclear warfare, pesticide-induced diseases, undesirable social impacts and suffering and death for animals, on the other.

The way we think about things is often shaped by ideas born and matured within scientific projects, while scientific questions are frequently situated and related to the philosophical debates faced by contemporary societies. Science prides itself on widening our knowledge of the world, but is the discovery of true propositions *always* a good thing? It can be argued that some scientific ideas, however well grounded, have harmed people or diminished their happiness by leading them to change or question their self-images, their aspirations and their self-conceptions. And though counter-intuitive, this assertion merits consideration (Forge 2008, pp. 149–151; Kitcher 2001, Chap. 12). In short, the many ways in which science affects us are impregnated with value issues, while the ethical and political responsibilities of scientific work and knowledge impact scientists and science as an institution.

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So what are the values manifested and expressed in scientists' behaviour and in scientific practices? How are they embodied in scientific institutions?[1] These questions should be contemplated in science education at all levels.

There are several compelling reasons for advocating teaching science and technology students the ethical and political questions they will have to address in their lives as professional researchers, designers and citizens. For example, values are implicit in the choice of research subjects and research methods. Philosophers, historians and sociologists have debated the scope and significance of values in science, including consideration of whether scientists are accountable for not anticipating the consequences of their enquiries. Kitcher rejects the "myth of purity" that assumes that "there is a straightforward distinction between pure and applied science, or between "basic research" and technology" (Kitcher 2001, p. 86). Forge (2008) argues that scientists can be held responsible for the foreseeable results of their research, whether the outcome is a technological object or a published paper detailing new information on a given phenomenon.[2] Rollin (2009) points out that the invasive use of animals in experiments presupposes moral choices. It could be argued (and it *has* been argued) that animals cannot or do not feel pain in the same way that humans do. Nonetheless, in psychological research, animals are used to model harmful or undesirable psychological states. Researchers are then confronted by a dilemma: if animals cannot feel fear, pain, addiction, etc. as humans do, then what would be the point of inducing that state in the animal? And if they can feel fear, pain, addiction, etc. as humans do, then why is it morally acceptable to induce those states in animals? Answers to this dilemma cannot escape an ethical dimension, i.e. that the knowledge gained from the experiment outweighs the discomfort, pain or death suffered by the animal. And what are the ethical and political dilemmas that should be faced in biomedical research on human beings? Serious issues about the different layers of vulnerability should be addressed by potential researchers (Luna 2009). Individual scientists choose to engage in certain kinds of research, while different societies and institutions (scientific or not) encourage some of them and discourage others (Forge 2008, pp. 179–183).

However, this chapter will focus on teaching the role of values in science at high school level. Several rationales have been given for bringing these issues into schools. For example, teaching and learning about the role of values in science in socio-scientific and controversial issues can play a role in humanising sciences and illustrating their ethical, cultural and political facets (Matthews 1994). It can help to foster an appreciation of the nature of science (Bell and Lederman 2003). It is dependent on and contributes to core abilities in reasoning, dialogue and argumentation (Simmoneaux 2008; Zeidler and Sadler 2008; Zohar 2008). Furthermore, it encourages a richer and more comprehensive construction of the

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[1] I would like to thank John Forge for his helpful suggestions on this paragraph and successive references to this point.

[2] For an interesting example, see the discussion on the Manhattan Project and especially on Frédéric Joliot-Curie's refusal to join the moratorium in publishing results on neutron multiplication in an assembly of heavy water, in 1939 (Forge 2008, pp. 72–76).

social and political aspects of science, avoiding trivialised images (Adúriz-Bravo 2005b). In the last couple of decades,[3] curricula in several different countries have regarded understanding of values-related issues as an important goal. Moreover, the consideration of ethical, political and other value outlooks in science content and research creates a particularly fertile ground for interaction between teachers of different curriculum subjects, such as natural sciences and philosophy (which has long been a high school subject in its own right in many countries)[4]. Even where philosophy is not part of the curriculum (not even as an elective course),[5] humanities subjects and civic and citizenship education offer many possibilities for collaboration, provided teachers adopt a controversial issues perspective rather than a more descriptive one (Kolstø 2008; Ratcliffe and Grace 2003). Appropriate teaching and learning of values-related questions in the nature of science should include involvement in reasoning and rational debate about controversial issues. Then, students can become more ready, responsible and adept at participating as citizens in science and technology-related issues both inside and outside their local communities, and even globally. Also, environmental, medical, biotechnological and telecommunication issues usually stimulate interest, so teaching science in socio-scientific contexts enhances motivation to learn the relevant scientific content (Grace 2006).

For science education, it is relatively easy to find interesting and relevant material from a socio-scientific point of view (SSI),[6] on the role of noncognitive values in the funding of scientific research and on the technological consequences of scientific inquiry. It is much harder, though not impossible,[7] to find related works framed in a more closely philosophical perspective. But philosophical reflection on values-related dimensions of scientific knowledge and inquiry has been on the increase in contemporary philosophy of science since 1970.[8] Philosophical debates have often distinguished cognitive (or epistemic)[9] values from noncognitive (non-epistemic, such as moral, political, economic) ones. The significance of cognitive values has become more or less commonly accepted, although there are several different standpoints on which constitute the relevant cognitive values and which should have precedence (Lacey 1999, Chap. 3). The place of noncognitive values, on the other hand, is much more controversial. For instance, different viewpoints can be found pertaining to the difference between the external impact of such values

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[3] AAAS (1993), Conseil de l'Education et de la Formation (1999), National Research Council (1996), and OECD (2001)

[4] Argentina, Brazil, (French-speaking) Canada, France, Germany, Italy, Mexico, Spain, Uruguay, etc. (UNESCO 2007).

[5] Usually, English-speaking countries such as Australia, (English-speaking) Canada, the USA and the UK.

[6] See, for instance, Sadler and Zeidler (2006), Zeidler and Sadler (2008), Zemplén (2009), also Kutrovátz and Zemplén (2014), Vesterinen, Manassero-Mas and Vázquez-Alonso (2014).

[7] For example, Davson-Galle (2002), Lacey (1999b, 2009), Machamer and Douglas (1999), Matthews (2009a).

[8] Douglas (2000), Dupré et al. (2007), Echeverría (1995), Kitcher (1993, 2001), Lacey (1999), Laudan (1984), Longino (1990, 2011)

[9] Throughout this paper we will take "cognitive" and "epistemic" as synonymous.

(on the funding or on the consequences of research) and the internal ones (the role of non-epistemic values in theory choice or theory validation, i.e. the presence of noncognitive values in science *content*).[10]

In sum, the thesis that science is not value-free has been steadily gaining acceptance. But this does not automatically mean abandoning every ideal of objectivity. Since the full meaning of the thesis that science is not value-free is the focus of heated philosophical debate, this chapter will aim first at presenting an overview of some issues pertaining to the role of cognitive values, and of the significance of noncognitive values on theory choice, validation or acceptability, from a philosophical point of view.[11] It will then address the question of why and how these philosophical issues and debates deserve to be engaged with in school science education.

33.2 Is Science Value-Free?

What are we speaking about when we discuss "values"? In the eighteenth and nineteenth centuries, a theory of economic value developed in the works of Smith, Ricardo and Marx, and even today, many people think of *economic* value when they hear the word "value". But the term has much wider scope: values (such as beauty, goodness, justice or sanctity) on one hand, and judgments of value on the other, have long been the focus of philosophical consideration.[12] Since the 1850s, debates conducted by philosophers and philosophical schools such as Nietzsche, Brentano, Dilthey, the utilitarists and the neo-Kantians at Baden have developed a theory of values that became a major concern in philosophy in its own right. The debates encompassed many issues related to the ontological nature of values; their scope; the existence of "intrinsic" values, as distinct from "extrinsic" ones; the notion of a polarity of values (for every positive value there is a related negative one); etc. (Ferrater Mora 1975; Frondizi 1982).

Although it isn't possible to address all these matters here, the question of the relationship of facts and values has led to a long-standing philosophical debate that has a special bearing on the central issue. It can be traced (at least) to Hume's discussion of the difference between matters of fact and matters of value: can *ought* be logically deduced from *is*? In some moral systems, reasoning goes from premises

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[10] I take SSI to refer to issues based on scientific results or practices that have an actual or potential relevant impact on society (Ratcliffe and Grace 2003). They may be considered either from the (frequently descriptive and explanatory) social sciences point of view (sociology, economy, anthropology, some theories of psychology, etc.) or from a philosophical (usually normative) standpoint (ethics, political philosophy, philosophical anthropology, aesthetics, etc.).

[11] Given that the emphasis is on a general overview of the issue and on the way science education in schools may address it, some philosophical depth will be inevitably lost. Interested readers can find that depth in many of the books mentioned in the references list.

[12] Many Platonic dialogues contemplate the nature and scope of specific values such as justice (first book of *Republic*), beauty (*Greater Hippias*, *Phaedrus*) or piety (*Euthyphro*).

that are related by "is" to conclusions where the components are connected by "ought". This inference seems to be "inconceivable". There have been multiple interpretations of the relevant passages, but the most common one has been to assume that no moral judgment and, more generally, no judgment of value ("ought") can be logically derived from a judgment of fact ("is").

The logical positivists and the logical empiricists, in the Humean tradition, were concerned with emphasising the distinction between facts and values, both in general and in relation to science. Values-related statements were deemed to be neither factual nor analytical statements, and therefore they lacked truth value. Ayer (1952) and Stevenson (1960) thought that they expressed emotions: acceptance, support and approval or else refusal, denial, and rejection. In the Anglo-speaking philosophical community, the stance that values are subject-related and that they express subjective preferences was prevalent in the first half of the last century, though philosophers of ordinary language contested the image of value statements as mere expressions of emotion. But it had a significant impact on the scientific community where it has been a widespread belief that since ethical (and other values) judgments have no empirical content, and therefore cannot be tested and verified, neither values clarification nor ethical debate of any sort has any relevance in science (Rollin 2009, 2012 calls this stance "scientific ideology"). However, this conclusion missed some of the points that positivist philosophers of science tried to make.

The value-free ideal maintains that science should be axiologically *neutral*. Mainstream epistemology and philosophy of science, until the middle of the twentieth century, had stated that science is supposed to be objective and rational in a strong sense, implying that it should depict the world as it *is* and not concern itself with how it *ought to* be. Therefore, scientific knowledge is not value-laden, since it aims at an empirically grounded understanding of the world. In the 1950s several factors started to undermine this position. On one hand, Quine's holism contested the idea of a precise distinction between statements of fact and statements of reason. Hypotheses cannot be confirmed (or refuted) independently, and there are no algorithmic rules for theory choice. So considering the *actual practices* of scientists when they decide on theory choice becomes more relevant than it had previously seemed. Later, Nelson (2002) built on Quine's arguments for holism to argue for recognition of the role of non-epistemic values in scientific practice.

In an influential paper, Rudner (1953) discussed the idea that the "scientist qua scientist makes value judgments" insofar as she must decide, for instance, when the evidence is *strong enough* to accept a hypothesis or how to balance simplicity against generality. Further discussions brought to the fore the role of the epistemic values. The context of discovery/context of justification distinction restricted context of justification to epistemic values related to logical soundness and empirical evidence and excluded subjective, social or contextual particularities. On the other hand, non-epistemic values (moral, political, economical, etc.) were still assigned to contexts of discovery or application, while deemed inadmissible as criteria for theory validation or theory choice.

Douglas (2000) explains how Hempel, in his 1965 essay, *Science and Human Values*, supports the idea that science should be pursued in such a way that only epistemic values have relevance with regard to hypothesis confirmation. But when we come to hypothesis *acceptance*, a proviso should be made concerning those instances that have direct consequences on practical issues (ethical matters, social impact, safety risks and so on). Inductive risk, the possibility that a confirmed hypothesis might be (ultimately) false, or that a rejected hypothesis might be (ultimately) true, gives cause for concern regarding the outcomes of a wrong decision.[13] In those cases, non-epistemic values become very relevant, by way of consequences and risk assessment. But in other cases of "pure scientific research", with no practical applications, epistemic values would suffice for hypothesis acceptance. From Hempel's point of view, not only the physical sciences but the social sciences as well should be conducted in accord with these principles.

At the same time, questions about the responsibility of scientists as individuals and as members of institutions became a matter of common concern, especially after World War II. From a sociological point of view, Robert Merton suggested that the *ethos* of science could be described as being composed of a small set of "moral" norms that summed up the ideals into which scientists (actual or in the making) are socialised: communalism, universalism, disinterestedness, originality and organised scepticism (Ziman 2003).[14] These moral norms express the values that govern the way scientific activity is run. They constrain practices and provide a standard against which they can be measured. Confidence in Merton's *ethos* has usually underpinned confidence in science and scientists as objective, honest and free of bias. But it has also undergone discussion and criticism. What is the role these values actually play? Further discussion, even by Merton himself, suggests that this ideal is normative, not descriptive: scientists should behave in accord with it, even if their primary motivations go a different way. However, in 1974, sociologist Ian Mitroff published a study on the ambivalence of norms within scientific institutions. Mitroff's research was based on a case study conducted with 42 scientists who were part of the Apollo mission. For every Mertonian norm, he proposed a counter-norm.[15] Mitroff posited that ambivalence is not only a characteristic of science but that it seemed necessary both to the existence and to the rationality of science (Mitroff 1974). In sum, a wide range of questions about the value-ladenness of science may be addressed both from inside and outside the scientific community. Debates develop in a theoretical, highly technical philosophical context, and also in a practical, widely public one.

For instance, recent philosophical discussions of mind–body relationship and the theory of actions are wont to explain human action as intentional, that is, in terms of beliefs and desires. We perform the action A because we desire to achieve E, and we believe that A is conducive to attaining E. So we may say that desires are one of the

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[13] Research on the safety of a new drug, for instance, may result in a false negative, with dangerous consequences for future users (see Douglas 2007, for an interesting example).

[14] There were also "technical" norms, pertaining to reliable empirical evidence and logical consistency.

[15] Emotional commitment, particularism, solitariness, interestedness and organised dogmatism (Mitroff 1974, p. 592).

causes of action. But individual desires do not stand alone: they are related to other desires (and beliefs) in a spreading network. Eventually, they depend on a person's basic beliefs and desires, that is, on the person's values. Discussing the fact–value dichotomy with regard to theory choice, Putnam (1990) states that terms such as "coherence" and "simplicity" are

> *action guiding* terms: to describe a theory as "coherent, simple, explanatory" is, in the right setting, to say that acceptance of the theory is *justified;* and to say that acceptance of a statement is (completely) justified is to say that one ought to accept the statement or theory (p. 139).

Therefore, values are a basis for action, particularly in terms of choice and decision. And they can become manifest in behaviours and expressed in practices both as personal and as social values (Lacey 1999).[16] If we try to explain how scientists choose between possible explanations of a phenomenon, we will eventually have to take values into consideration.

33.3 Science and Values

In the last half century, questioning of the idea of value-free science has raised many important issues in philosophy of science: realism, rationality, objectivity, demarcation, scientific change, scientific controversies and the role of gender, race or class (Doppelt 2008; Dupré et al. 2007; Machamer et al. 2000). It also has a significant role in discussions on applied science, technology, Big Science issues (such as trust and authority) and risk assessment. Even without rejecting empiricism and some conception of objectivity, science content and scientific activity (and not just its consequences) may be regarded as value-laden.[17]

With Kuhn's *Structure of Scientific Revolutions* (1962) a turning point was reached. Along with the renewed interest in the history and actual practice of science came the notion that values (whether those of society, scientific communities or individual scientists) have a relevant part to play. They are present not only in the choice of problems and in the technological or applied aspects of science but also in the evaluation of hypotheses, in theory choice and in conceptual change, which cannot be described simply in terms of logical inferences. A heated discussion ensued regarding whether the presence of noncognitive values resulted in less objectivity, leading to downright relativism.

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[16] Lacey (1999) states that personal values may be *manifested* in behavior, *woven into* a life, *expressed* in a practice, *present* in consciousness, *articulated* in words and *embodied* in social institutions and in society (pp. 25–6). Social values are *manifested* in the programmes, laws and policies of a society; *expressed* in its practices; *articulated* in histories, traditions and institutions; *woven into* a society when they are manifested constantly and consistently; and can be *personalised* when persons act on behalf of a society where particular values are embodied (pp. 28–9).

[17] Kitcher (1993), Lacey (1999), Longino (1990), Machamer and Douglas (1999), and Wylie and Nelson (2007)

That science is value-laden is now accepted by most philosophers of science, although the scope of this assertion should be clarified. The Hempelian distinction between hypothesis confirmation and hypothesis acceptance is still part of the debate. The thesis that only cognitive values are necessary for scientific knowledge[18] clashes with the notion that other noncognitive values are constitutive of proper scientific practice. Cognitive values may be regarded as constitutive of theory choice both with regard to s*ignificance* requirements (choice of problems, selection of hypotheses and theories) and in connection with *confirmation* requirements (assessing the relevance of the evidence supporting hypothesis or theories) (Carrier 2012). But does science exclusively aim at understanding the world, or is scientific knowledge inextricably entangled with the purpose of making objects or solving problems? Is there a multiplicity of possible goals interacting within scientific inquiry (such as maximising human happiness, or economic profit, or political success)? Even if the answer is weighted towards understanding, noncognitive values are still in evidence.

Dupré and colleagues (2007) suggest that arguments against the idea of a value-free science may be categorised into three main groups: "(1) arguments from denying the distinction between fact and value, (2) arguments from underdetermination, and (3) arguments from the social processes of science" (p. 14). The first set criticises the possibility of a clear demarcation between fact and values, either by offering counterexamples or by theoretical discussion against the independence of both terms. The second group alludes to underdetermination either of theory by data or of theory choice by epistemic values, drawing from the original Duhem-Quine thesis and from Kuhn's claims, respectively (Carrier 2012). The third set encompasses different studies aimed at showing how scientists interact among themselves and with society at large and how values, interests and commitments shape these interactions. As is usually the case with classifications, this one may help us organise the multiple discussions on the field, but it is not supposed to cover all possible standpoints on the value-ladenness of science (see discussion of Lacey's arguments below, for instance).

Dupré and colleagues also suggest four dimensions that appear in philosophical debates with regard to values: the *kind* of values involved, the *way* in which they are involved, *where* they are involved and what are the *effects* of their involvement. As for the kind of values, the distinction is usually made between cognitive values, directly related to truth and knowledge, and noncognitive values, such as moral or political ones, though this distinction is itself subject to debate. There is no agreement on which values should be included under the labels of "epistemic" or "cognitive" and what the standards for their application are or the relative importance of each one. For instance, in reworking Kuhn's 1977 list, McMullin (1982) proposes predictive accuracy, internal coherence, external consistency, unifying power,

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[18] Space precludes discussion of this position here. For a survey of the relevant arguments, the reader is referred to Doppelt (2008), Haack (1993), Laudan (1984), and McMullin (1982, 2008). The very distinction between epistemic–non-epistemic values has been discussed at least since Rooney (1992).

fertility and simplicity. Doppelt enumerates: "epistemic values include properties of theories such as simplicity, unification, accuracy, novel in prediction, explanatory breadth, empirical adequacy, etc." (Doppelt 2008, p. 303). Lacey (1999) reviews a list of items suggested by a range of authors: empirical adequacy, explanatory and unifying power, power to encapsulate possibilities, internal consistency, connectivity or holism, inter-theory support, source of interpretive power, puzzle-solving power, simplicity and fertility.

How are values involved? A first question to address is whether the involvement is unavoidable (essential) or only possible. And, in the latter case, whether it is something to be avoided, i.e. whether value-laden science is bad science. Where are values involved in scientific inquiry and knowledge? The authors discern three broad areas of science: the fields under research, the hypotheses that are posed and the evidence that is taken to support one hypothesis over others and, finally, the use of these results to generate explanations. In the first case, a division is made between the natural and the social sciences, in the sense that it could be possible in principle to investigate in a value-free way in the first group but not in the second. Or values (both epistemic and non-epistemic) would be present in funding decisions: choosing which projects to fund implies evaluating both the soundness of the proposal and the priorities of the government or agency providing the funding. A deeper consideration goes into establishing the entities that populate the area to be researched. Also in explanations, the choosing of one factor over the (multiple) others as *the* cause of a phenomenon may be determined by value considerations (Longino 1990). In the second question, there is a particularly sensitive point: if non-epistemic values have a bearing on the selection and confirmation of hypotheses, then the term "value-laden science" acquires a much stronger meaning than in the previous cases. Lastly, what would be the effects of a value-laden science? The authors state that given the variety of issues and the multiple possible positions, this question will have many answers, related to the different ways in which values may be involved in science.

33.4 The Value-Ladenness of Science: Some Philosophical Perspectives

The following reviews a few examples of relevant philosophical approaches to the question of value-ladenness with regard to noncognitive values.[19]

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[19] There are many interesting approaches to this problem in the recent literature in philosophy of science. Because it would have been impossible to address even a representative selection, three have been selected as a first approach to the range of views expressed. See Doppelt (2008); the papers in Dupré et al. (2007), Kitcher (2001), and Laudan (1984). Also, Douglas (2009) *Science, Policy and the Value-Free Ideal*, University of Pittsburgh Press, and Machamer and Wolters (2004) *Science, Values and Objectivity*, University of Pittsburgh Press.

In *Science as Social Knowledge* (1990), Longino sets out to address the relationship of science and values in the terms of her *contextual empiricism*. She calls it a "modest" empiricism related above all to epistemology and the notion that knowledge depends on experience, and much less to metaphysics (see later discussion). *Experience* constitutes the basis for knowledge claims, coupled with an emphasis on *context* in a twofold sense: with regard to background assumptions to reasoning; and to the cultural milieu in which scientific inquiry takes place. Data cannot be considered as evidence per se: whether some fact or state of affairs will be considered relevant evidence is determined not with reference to natural relations but in connection with background assumptions. These may convey, on one hand, "constitutive values" internal to science and expressing cognitive virtues; and on the other hand, "contextual values" expressing social or practical interests. Background assumptions introduce contextual values into proper scientific inquiry: contextual values "guide interpretations and suggest models within which the data can be ordered and organized" (1990, p. 219). Their presence is not the consequence of methodological limitation or error: it does not imply bad science. Nonetheless, methodology does have a role to play: not all values are admitted without restrictions. Judgment about data changes when the meaning of terms is adjusted, but if the meaning were the same, the same earlier judgments would be made. Also, observational judgments may change places regarding their significance within a theory when assumptions change. Then, central judgments may become peripheral, and previous seemingly unimportant judgments may become significant.

Hence, we can discern an empirical dimension of science, concerning evidence retrieved from observation and experiment, and a theoretical dimension of science. Both are linked by evidential reasoning: reasoning from and to data and hypothesis. Reasoning is understood by Longino as a practice. It is not mere decontextualised computation, but an interaction that takes place in a context. And hypothesis may also change when contextual assumptions change: there is interaction between background assumptions, general theoretical perspectives and experience.

Longino emphasises the differences between her outlook and those of positivism and realism: observation and reason on their own are not enough. They are supported by assumptions that express social and cultural values. But she also distinguishes her position from the relativism linked to holism: not all statements are context relative in the same way. The role of social and contextual values does not rule out objectivity. The scientist's desires for some kind of knowledge may configure the objects of her inquiry, but the existence of background assumptions that introduce social and contextual values becomes a basis for relativism only in an individualist conception of scientific inquiry. Scientific inquiry is the undertaking of a community, and not of individual researchers. It depends on the collaborative social interactions of "transformative interrogation". In this way, the impact of subjective preferences is minimised through criticism and interrogation by the scientific community. The more diverse and heterogeneous the community, the more diverse their assumptions will be. More of them will be made explicit, scrutinised and eventually modified. Discovering where inferences and experiences differ presupposes a minimum communicative context: shared standards for criticism, recognised public forums for its presentation, community responses and an equality of intellectual authority (Longino 1990, pp. 76–81). This also leads Longino to support a minimalist realism: "there is a world independent of our senses with which those senses interact to produce our sensations and the regularities of our experience"(Longino 1990, p. 222). Criticism and interrogation go a long way to minimise the impact of assumptions, but they cannot eliminate them: those assumptions shared by all the members of the community will not be made explicit; they will remain invisible and thus evade examination.

Furthermore, and directly relevant to science education aims, Longino states that the view that science is value-neutral may have the undesirable effect of disempowering non-scientists from understanding not only the technical, disciplinary content of inquiry that inform technologies but the contextual dimensions that shape inquiry. So they will have fewer possibilities of being adequately critical when dealing with the products of those technologies (Longino 1990, p. 225).

Lacey (1999, 2009) partially agrees with Longino's thesis, insofar as cognitive and noncognitive values may be clearly distinguished. Science should aim at empirically grounded and confirmed knowledge and understanding of phenomena. Inside these limits, it may be conducted within a plurality of worldviews and their associated value outlooks. "Science is value-free" is not meant in the sense that science and values don't touch. Science itself can be regarded as a value (as far as knowledge is a value); value judgments may be informed by scientific knowledge of the relationship between means and ends; scientists must display personal and moral values in their scientific practices (the "ethos of science"); and so on. However, these interplays should not touch the three component notions: impartiality, neutrality and autonomy. Neutrality means that scientific theories and practices do not imply or favour any value judgments or outlooks, cognitively or with regard to applications. Impartiality entails that criteria for the appraisal and acceptance of theories or the making of scientific judgments should not include noncognitive values. Autonomy asserts that scientific communities claim sole authority in the choice of problems, the evaluation of theories, the content of scientific education and in prerequisites for being admitted to the scientific community.

Lacey revises these three notions. Impartiality presupposes that cognitive and noncognitive values can be discriminated. Theories are accepted if and only if they display cognitive values to the highest degree, in agreement with relevant empirical data and other accepted theories. They should be subject to the most rigorous standards of evaluation. Neutrality presupposes, first, impartiality. Also it entails that there are accepted scientific theories that are significant for every viable value outlook and that no value outlook is noticeably favoured by accepted scientific theories. The notion of *value outlook* means that different kinds of values (moral, social, political, etc.) may be ordered coherently and rationally founded by a set of presuppositions about nature and human nature and about what is possible. Such presuppositions may be scientifically investigated to some extent. Inquiry may then support or oppose the presuppositions of a given value outlook. So, for a value outlook to be *viable*, it must be in accord with the results of accepted scientific knowledge. Scientific knowledge constrains the range of viable value outlooks, but still leaves a plurality of them open to explore. Lastly, autonomy is subordinated to impartiality and neutrality. Accepting a theory implies exclusively the play of cognitive values. But since the previous moment of adopting a strategy leaves an important role for social values to play, autonomy cannot be well embodied.

Modern science has been predominantly associated with a particular worldview: materialism. This has led to science being conducted under a certain strategy that constrains potentially admissible theories to those that can

> represent and explain phenomena […] in terms that display their lawfulness, thus usually in terms of their being generated or generable from underlying structure and its components, process, interaction and the laws (characteristically expressed mathematically) that govern them (Lacey 2009, p. 843).

Consequently, empirical data are chosen and reported typically in terms of quantitative categories, related to measurement and instrumental and experimental operations. Both data and theoretical representation of phenomena are "stripped of all links with values and dissociated from any broader context of human practices and experience" (Lacey 2009, p. 843). Lacey calls this way of conducting science the "decontextualised approach" (DA), which is associated with the "modern value scheme of control" (Lacey 1999b). Materialism is widely associated with the values of technological progress (VTP) that favour control of natural objects. This way of conducting science means that science is not neutral, but it can still be impartial, as long as cognitive and social values have a role in scientific judgments at different logical moments (i.e. adopting a strategy or soundly accepting a theory). But carrying out science within the DA is not the only possibility of conducting science impartially. The exclusive association of scientific research and materialism must be challenged not only in philosophy of science but in sound science teaching as well. With regard to applied science and technological innovation, DA may be useful to explain its *efficacy*, but it is certainly not enough to establish its ethical or political *legitimacy*. There is an interest in conducting systematic empirical research under other strategies which do not uphold materialism. For example, Lacey discusses how genetically engineered transgenic crops, produced under DA and in accord with VTP, differ from organic or ecological agricultural alternatives. These alternative strategies privilege sustainable ecosystems, agency and community and, therefore, different socio-economic relations of production (Lacey 1999, 2005, 2009).

Neutrality (in the sense discussed above) is better served by a plurality of strategies that address the interests of different value outlooks, instead of reducing options to the materialist strategies which exclude value-laden terms from theories and methodologies. Nonetheless, admitting a plurality of options does not support any or every worldview and value outlook, which may mean abandoning impartiality. For instance, religious outlooks inconsistent with accepted scientific results, such as intelligent design, are incompatible with the scientific attitude.

Spanish philosopher Echeverría (1995, 2008) characterises scientific activity as a value-laden transformation of the material world and of human beings. He proposes a variation on Reichenbach's distinction between context of discovery and context of justification into a new categorisation of four contexts: innovation, evaluation, application and education. Contexts of innovation and evaluation loosely resemble the original proposal of Reichenbach. However, context of evaluation widens to comprise the different practices scientists perform when they evaluate products of scientific activity as they are achieved: not only hypotheses and theories but also data, measurements, experiments, proofs, papers and other publications. Context of application relates to science-related activities that aim at attaining changes in the world. This includes the manufacturing of artefacts but also the modification of images, languages and social relationships. Expert consultation in problem solving is also part of this context. Context of education consists of two reciprocal activities: teaching *and* learning, not only of conceptual and linguistic systems but also of representations, scientific images, notations, operating techniques, relevant problems and instrument handling procedures.

Echeverría advocates for axiological pluralism in science: scientists share a common collection of values, practices, habits, goals and, of course, knowledge. Scientific practice is axiologically meliorative: new actions improve on previous actions because they increase the degree of satisfaction of some value or decrease some disvalue. Different contexts imply different activities and agencies (educational, investigative, evaluative and application-oriented). Therefore, axiological rationality does not exclude conflict of values, but it requires specific procedures for its resolution.

Core values may differ in scientific practice in different contexts. For instance, science teaching and learning hold their own criteria and procedures for enunciation, justification, evaluation and application of scientific theories, which may occasionally diverge from those present in other settings of scientific activity. It does not entail mere transmission of information or even knowledge. In the context of education, the main value is "*communicability* of scientific content to every human being and therefore a requirement for publicity"[20] (Echeverría 1995, p. 125). Scientific content alludes to knowledge but also to skills and abilities. And also, and here we find an occasion of tension, on one side it should aim at the normalisation of those knowledge, skills and abilities, but on the other it should foster freethinking, criticism and creativity. Furthermore, within the context of education itself, criteria for evaluation of popular communication of science may differ sharply from those of investigative or academic education. Therefore, education becomes a pertinent frame for the philosophical consideration of the historical and conceptual development of scientific content and practices, and of the interplay and conflict of values within them.

33.5 Science, Values and Science Education: Two Debates

While the foregoing outlines some of the richness and relevance of the question of values in contemporary philosophy of science, it is important to consider how philosophical discussions about values and science relate to science education.

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[20] "…la *comunicabilidad* de los contenidos científicos a cualquier ser humano; de este se deriva la exigencia de publicidad"

This section begins by synthesising some interesting debates in two special issues of *Science & Education* (1999, 8(1) and 2009, 18(6–7)) to illustrate some of the questions at stake. Both publications share the same structure: an author posits a thesis on a controversial philosophical and metascientific question, and a number of colleagues respond to that core article. Authors come from diverse professional origins: philosophers, scientists, educators and historians engage in multidisciplinary interchange. Finally, the first author makes a synthesis and response to the critics or to the alternative viewpoints stated.

Many of the topics addressed in the first special issue (*Science & Education*, 1999, 8(1)), under the title *Values in Science and Science Education: A Debate*, concern philosophical discussion about the relationship of science and values, as outlined above in the *Science and Values* paragraph. Discussion here highlights the relevance of these issues to science *education* and readers are advised to refer to the actual papers for deeper understanding of the philosophical points. The first round of debate starts with a paper by Lacey (1999b). He states that different standpoints on human values and human flourishing may affect the strategies under which science is conducted. So, science education should foster not only a sound understanding of science knowledge and practices but a critical self-consciousness about scientific activity and applications. This means understanding how cognitive and social values interact in scientific activity, what the limits and risks of that interaction in the making of theoretical judgments are and how noncognitive values may affect the achievements of scientific inquiry. This understanding should also encompass the knowledge and evaluation of different points of view. For example, this would mean challenging the exclusive association of scientific research with materialism within science education. Debates should include not only scientific practices and results under the materialist strategy but also the desirable strategies to further human well-being. This, however, would not mean accepting those worldviews or value outlooks that clash with the scientific attitude, such as creationism. Also, Lacey still upholds, as a main goal of scientific education, the teaching of scientific knowledge, the methods for discovering and the criteria for evaluating it obtained within DA. This may even constitute the core of first approaches and experiences with science learning (Lacey 1999, 2009).

As Machamer and Douglas (1999) and Davson-Galle (2002) emphasise, Lacey's position entails making the values that inform science knowledge and research explicit so that alternative value outlooks become visible and evaluation becomes possible. In a response to Lacey's paper, Cross (1999) indicates that these suggestions for science education belong within a rich tradition of like-minded proposals from different ideological perspectives. He points out that Lacey's call for sound and critical understanding of scientific activity and applications may be interpreted in two different ways. On one hand, it may be thought of as a somewhat insufficient proposal to discuss science from within a "traditional conception of scientific literacy". This option entails the difficulty of integrating these metadisciplinary aspects of science in the science curriculum, where they tend to be relegated to the periphery as mere illustration, and traditional content and values will still constitute core science teaching. Alternatively, he recommends a more "transformative" scheme to initiate a thorough revision of science education in schools in order to promote citizens' engagement and participation.[21] In his *Reply*, Lacey agrees with the desirability of teaching science in such a way that it enables an integration of the philosophical, historical, economic and social context of science. This would mean favouring a richer understanding of science for those who will go on to be active scientists, but also for those who will not but still need to be able to judge the significance of scientific research and knowledge with regard to cognitive and social values.

Though not directly referring to Lacey's paper, Allchin (1999) discusses the relationship of science and values with an emphasis on the educational point of view. He argues for science teachers to explicitly address the various ways in which values and science may intersect: epistemic values in scientific research; non-epistemic values in individual practitioners of science and methodological provisos against potential biases; and social and cultural values' challenges and novelties deriving from scientific results. Teachers should help students develop the relevant skills for a critical consideration of these roles of values in science. And he argues that this will be best achieved through reflexive analysis of students' own "modest" scientific modelling practices in classrooms and of historical cases. Reflexive analysis may also foster argumentative skills oriented to public rational justification of values (ethical or otherwise) avoiding common sense, naïve recourses to individual, personal "feelings" or values.

The second *Science & Education* issue we will consider, *Science, Worldviews and Education* (2009, 18(6–7)), has a much larger scope than the first one, since the idea of "worldview" encompasses not only values-related questions but also metaphysical, ontological and epistemological standpoints (see Chap. 50). The focus here is on some arguments linked to the relationship of values and science and its consequences for science education.

What is a worldview? If we accept that worldviews imply ontological, epistemological, ethical and sometimes religious commitments, is there a scientific worldview or is science worldview neutral? How does science engage with religious, philosophical, ideological or cultural worldviews? How do philosophical systems relate to science (and the putative scientific worldview)? What are the educational consequences of these questions? Should science education inform student worldviews, promoting worldview-related beliefs and ways of life or should science be learned only for instructional purposes? Should they promote students' *acting* upon those beliefs and ways of life? Some of these questions aim for descriptive, factual research; others require normative, regulative argument.

The lead essay by Hugh Gauch, Jr. (2009), delineates seven key features or "pillars" of science, derived from AAAS and the US NRC position papers: realism, the presupposition that the world is orderly and comprehensible, the role of evidence, use of logic, the limits of science, the universality of science and its ambition to contribute to a meaningful worldview. Reasoning from those "pillars", and from a

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[21] See Kutrovátz and Zemplén (Chap. 34), and Vesterinen, Manassero-Mas and Vázquez-Alonso (Chap. 58), for a discussion on research in sociology of science and science education and of STS and HPS traditions in science education. Also, Aikenhead (2006), Hodson (2011), and Pedretti et al. (2008).

discussion of scientific method, Gauch argues against naturalism as a necessary commitment for science[22] that "the presuppositions and reasoning of science can and should be worldview independent, but empirical and public evidence from the sciences and humanities can support *conclusions* that are worldview distinctive" (p. 667, emphasis added). So, science does not imply distinctive worldview beliefs. Scientism is unacceptable. While science can say something about worldviews, it is not the exclusive provider of knowledge; philosophy, religion and art can offer it, too. This means that natural theology is not impossible in principle: empiric scientific evidence may address conclusions that derive from non-natural premises. So, from Gauch's standpoint, worldview-specific implications have a place in individual beliefs and in public debate, but not in institutional (including educational) requirements. In his paper, Fishman (2009) agrees that science does not presuppose naturalism as an a priori commitment, and therefore, science can evaluate supernatural theses or claims as far as evidence supports them. So, the rationale for not teaching intelligent design as an alternative to evolution in public schools (for instance) rests on the basis that evidence does not support it, regardless of whether it is labelled as "natural", "supernatural", "religious" or "paranormal".

An interesting historical illustration of the relationship between a theistic worldview and a demand for empirical evidence to support belief may be found in Matthews' article on the life and works of Joseph Priestley (Matthews 2009a). Irzik and Nola (2009) oppose the idea that science can be worldview independent: since a "pillar of science" answers a worldview question, and it also contradicts other possible answers (other worldviews), it cannot be assumed to be worldview independent. For example, they contend that Gauch presents methodological naturalism as a "mere stipulatory issue", while they claim it to be one of the "essential and distinctive features of science": abandoning it is tantamount to abandoning science (p. 741).

However relevant this discussion, worldviews issues should not be reduced to metaphysics questions such as the existence of God or the purpose of the universe. Irzik and Nola (2009) present a series of questions worldviews seek to provide answers for. Among them are questions such as "How should we live our lives?" "What is good and bad, right and wrong?" and "What is the best form of government?" that deal with ethical and political issues. The authors argue that it is possible to offer naturalistic answers even to these questions.

Do worldviews necessarily imply particular value outlooks? What are the consequences of adopting a scientific worldview for the understanding of moral behaviour? What are the consequences for the conduct of science in adopting value outlooks associated with non-scientific worldviews?

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[22] For the sake of concision, we will refer to methodological naturalism as claiming that natural entities and means only can be called upon in scientific knowledge and practices and that natural sciences are a paradigm of epistemic research. This does not exclude by itself the existence of supernatural beings. Ontological naturalism states that only natural entities *exist* as a content of reality and no supernatural explanations whatsoever are acceptable. Irzik and Nola (2009, p. 733) point out that in some versions of naturalism, mentalistic and even mathematics items can be legitimately involved, since "natural" not necessarily implies "physical". Finally, materialism or physicalism affirms that only *material* (i.e. physical) entities exist.

The relationship between religion, philosophy and science (or natural philosophy) has long been the object of examination. It fuelled heated philosophical debate in the Middle Ages and has been a leitmotif in studies of the Copernican Revolution. Also, evolution-related issues frequently involve arguing on this relationship. Recently, Stephen Jay Gould coined the acronym NOMA to refer to one of the stances in the debate: the idea that science and religion each has a legitimate *magisterium* or teaching authority (from *magister*, Latin for "teacher"), and these *magisteria* do not overlap. Science has nothing to say about the domain of ethics, while religion rightfully deals with questions of ultimate meaning and moral value. Furthermore, scientific and religious *magisteria* do not exclude other possible inquiries (for instance, philosophical ones).

On the other hand, it may be argued that deciding which theories belong in the scientific canon and whether they have worldview content is something that cannot be determined necessarily or a priori (Cordero 2009, pp. 757–8). In fact, the limits for scientific understanding of the world (Gauch's Pillar 5) change over time. The scope of naturalistic perspectives, such as Darwinist theory of evolution, has been widened to explain human mind and culture, including political and moral issues. Sociobiology and evolutionary psychology endorse the idea of a naturalistic approach to ethics and moral behaviour. For instance, Ruse and Wilson (2006) contend that offering materialistic explanations for the basis of human culture and human mind undermines the foundations of any a priori philosophical or religious (extra material) ethics. Evolutionary biology and cognitive psychology may be expected to explain feelings of right and wrong, and so offer a basis for morality; "a naturalistic ethic developed as an applied science" (Ruse and Wilson 2006, p. 558). But showing the links that go from factual premises to normative conclusions (from *is* to *ought*) is harder than it seems: "the connections between biological facts and questions about the status of morality are extremely complicated" (Kitcher 2006, p. 181)[23]. This cautions us against assuming that the relationship between biology and ethics in questions pertaining to, for instance, moral objectivity or moral progress, has been addressed in a way that does justice to its complexity. But it does not mean discarding research aimed at connecting biological knowledge and moral philosophy. Cordero (2009) argues that scientific content and scientific methodology can establish some constraints on which worldviews should be marginalised.

Conversely, a case can be made to show how religious worldviews imply an associated value outlook that includes a set of moral imperatives, some descriptive and normative framework of the mutual relationships of human beings and of human beings and nature. And Fishman argues (2009) that this poses a renewed challenge to science educators: how to maintain the desirable intellectual integrity without offending students in a way that impedes science education. Also, Reiss (2009) focuses on scientific and religious comprehensions of biodiversity to show how science and religion can be seen as distinct or related worldviews, depending on the aims of school science education. Arguments may be raised for and against

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[23] See his outline of three meta-ethical questions for an example of how complicated this can become.

teaching about religion in science classes. Reiss reviews some of them, and contends that science teachers can be respectful of students' personal positions while at the same time fostering their engagement with science and helping them understand the strengths and limitations of science with regard to specific issues.

33.6 Science Education and Philosophy Education: Teaching Controversial Issues

Even with the previous brief summary, it can be seen that teaching about the role of values in science content and practice may present diverse challenges to science (and other) teachers. Certainly, it will seem controversial to those who still think science teaching should aim at the transmission of facts and the scientific method (or methods), and to those who think of science as value-free. They will probably argue that ethical, aesthetic, political or social issues are simply not relevant to science teaching. Even cognitive values may not be easily identified or taken into consideration by science teachers (Figueiredo Salvi and Batista 2008). Furthermore, those who are committed to taking nature of science into consideration in their classes may find it hard to decide how much time to devote to values-related issues. Teaching controversial issues with an acceptable degree of depth might take too much time, detracting from "regular" scientific issues demanded by the curriculum. This could be perceived to be a loss to "real" scientific content, and not even central to nature of science teaching. Also, value issues imply taking into consideration a multiplicity of variables: incomplete or insufficient information, uncertainty and risk, multiple and sometimes incompatible ethical and political philosophical, psychological and sociological frameworks (Ratcliffe and Grace 2003; McKim 2010). Science teachers may feel daunted by this complexity. Some of them may feel uncomfortable with their lack of information or expertise regarding such issues as ethical or political theories, or moral reasoning. And they may not have adequate resources and strategies to cope with the teaching of open-ended issues. Also, teachers may feel concerned about being suspected of bias or of having a hidden personal or political agenda. Some issues may be "too" controversial in particular institutions, for instance, those that collide with religious faith, which is the case with many bioethical questions such as abortion or stem cell research (Grace 2006). So why bring value issues into the science classroom?

Nowadays the idea that the aims of science education should include teaching some significant scientific knowledge along with some metascientific knowledge and understanding about the nature of science is broadly accepted. It has long been argued that the purposes of science teaching at school level must expand from the traditional initial training of the next generation of scientists. It should involve preparing students who will not go on to a scientific career for a more ready, responsible and adept participation as citizens in scientific and technologically related issues. In a well-known work, Driver and colleagues (1996) stated five rationales for teaching about the nature of science, two of which are relevant here: the democratic argument and the moral argument. On one side, students should leave school with enough understanding of scientific knowledge and practices that they may be able to appreciate and engage with the dilemmas posed by value-laden ethical, political and socio-scientific issues. On the other, they should develop a significant awareness of the norms that guide the activities of the scientific community, norms and values that are of general worth. Students should be able to explore their own (frequently tacit) knowledge, beliefs and values, and learn to assess science and technology knowledge and artefacts with regard to individual, social and global responsible action concerning that knowledge and those artefacts. Also, ethical and citizenship education is an educational aim that can be enhanced by including reflective consideration of the traditional Mertonian values, the so-called countervalues (Mitroff 1974), and other epistemic and non-epistemic values in scientific practice.

The teaching of the role and impact of contextual values, especially with regard to biotechnology and environmental challenges, has been fully addressed in the SSI literature,[24] and it is not possible to review it here. Discussion here focuses on some questions related to ethical issues and education that have been brought to the fore both in science and in philosophy education from a philosophical point of view. This does not imply teaching philosophy of science (or philosophy in any other sense) in the science classroom as a pure discipline (Adúriz-Bravo 2001; Matthews 1994/2014).

Although from a philosophical point of view it would be difficult to find any accord on the nature of science, from the standpoint of the wider community of science education (including philosophers but also historians of science, sociologists, natural scientists, science educators, science communicators, policymakers, science teachers), a corpus of themes or strands worth teaching on the nature of science can be found. And values-related issues regularly appear in this corpus.[25] Furthermore, noting that this description is intrinsically problematic (but not arbitrary) may encourage a richer and more comprehensive construction of the ethical, social and political aspects of science. In this way, "straw-man" perceptions of science as a deceiving harbinger of oppression, or as a faultless and providential supplier of truth and human progress may be avoided or at least discouraged (Adúriz-Bravo 2005b). Kitcher (2001, p. 199) describes these two images as (i) the version of the faithful, "which views inquiry as liberating, practically beneficial, and the greatest achievement of human civilization", and (ii) the image of the detractors that portrays science as "an expression of power, a secular religion with no claims to "truth," which systematically excludes the voices and the interests of the greater part of the species".

On the practical side, many curricula from different countries[26] regard understanding of values-related, socio-scientific and ethical issues as an important goal.

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[24] Jones et al. (2010), Ratcliffe and Grace (2003), Zeidler and Sadler (2008), Sadler and Zeidler (2006), Zeidler and Keefer (2003), Zemplén (2009), also Kutrovátz and Zemplén (2014).

[25] Adúriz-Bravo (2005b), Osborne et al. (2003), and Lederman et al. (2002)

[26] Among others, AAAS (1993), McComas and Olson (2002), Conseil de l'Education et de la Formation (1999), National Research Council (1996), OECD (2001), Consejo Federal de Cultura y Educación (2006), and Secretaria de Educação Básica Brasília (2006).

Also, many of these issues occupy a relevant space in the media. They are present in social and political debates, and even day-to-day subjects of discussion, decision-making and social and political participation. The topics may range from global dimensions (e.g. nuclear plant safety, which was lately in the news after the Fukushima Daiichi incident), to regional or national dimensions (for instance, grandparent's DNA evidence in determining the filiation of the *desaparecidos* (Disappeareds') offspring in Argentina), to personal decisions (shall I vaccine my children against H1N1 influenza or MMR?). Science teachers may help students acquire the relevant scientific information that has to be considered in these controversies. They may provide conceptual and procedural knowledge that enables students to evaluate scientific content, distinguishing mere opinion from well-substantiated evidence. They may highlight the importance of sound scientific knowledge to appraise the premises in the arguments provided, therefore inspiring new interest in the relevant scientific content. Students would then become acquainted with a more accurate portrait of the nature of scientific activity and the work of scientists, and develop a more sophisticated awareness of the scope and limits of scientific knowledge that will help them to evaluate the reasons provided and the conclusions arrived at.

Conner (2010) proposes another rationale: the appreciation of cultural determination of the solutions to ethical problems. This would help "develop tolerance and an appreciation of other viewpoints". Some questions can be noted here. For instance, we find again the normative–descriptive choice of stance. What is and what should be the relationship between philosophical ethics and social sciences empirical research? What *empirical* psychological or social traits do philosophical ethics theories presuppose? Are they sound? What do anthropological or sociological differences between cultures tell us about the different values embraced and the distinctive ways of resolving conflicts? What are the *normative* principles about truth, duty, happiness, a good life and justice? What are the different perspectives on toleration and rights that may apply?[27] On one hand, philosophical ethics or theory of knowledge may be supported and influenced by empirical findings (though some philosophers will argue that this influence is inappropriate). On the other, empirical research may be shaped by (sometimes tacit) philosophical frameworks. This can be extended to the teaching and learning of ethics (in science classroom and elsewhere): should we present different ethical perspectives and help students make informed decisions about them? What would be the impact on actual behaviour? Should teachers aim at the internalisation of specific moral codes? Or should they present a plurality of moral systems and a diversity of ethical theories and help students develop the requisite skills and attitudes conducive to making autonomous, reflective choices? Ethics teaching in a vocational education setting, for instance, would strongly aim at an impact on students' beliefs and behaviour. Discussion on research ethics in most scientific schools, of the moral status of animals in Veterinary school, or reproductive ethics in Medical school (particularly in Obstetrics and

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[27] For a first approach to the philosophical problems posed by the notion of tolerance, see Forst, R. (2012), Toleration, In E.N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Summer 2012 Edition, forthcoming). http://plato.stanford.edu/archives/sum2012/entries/toleration/.

Gynaecology) (Gillam 2009; Rollin 2009), for instance, will aim at fostering behaviour and exceed the understanding of ethical theories and the training in ethical reasoning typical of Humanities education.

Reiss (2008) enumerates four possible aims for teaching ethics in the science classroom: heightening students' ethical sensitivity, increasing students' ethical knowledge, improving students' ethical judgment and making students better people. Increasing student knowledge does not necessarily imply moral transmission. Moral transmission aims at the internalisation of a set of principles, values and rules. It implies the choice of a particular value outlook and a specific conception of the good life; it intends for students to adopt that outlook and that conception, and act accordingly. Ethical inquiry approaches, instead, aim at helping students develop the requisite skills and attitudes conducive to making autonomous, critical and reflective evaluation and choices on specific values, actual moral codes and ethical dilemmas (Gregory 2009). Since there is no philosophical consensus regarding the relationship of values and science, a plurality of views can be addressed. However, this standpoint requires a certain engagement with a minimal set of moral principles and does not imply a relativistic stance. From a Habermasian point of view, for instance, it would presuppose the requisite conditions and rules to conduct a genuine dialogue, that is, rational argumentation as the only authority, open choice of problems, unrestricted participation of any interested party that can make a relevant contribution, no coercion exercised, equal possibilities for everyone of expressing themselves and everyone being internally free to be honest and not deceive others or oneself.[28]

Political literacy, as an indispensable stage in the development of a democratic society, presupposes an education that, among other things, fosters skills related to rational deliberation and argumentation in the elucidation and resolution of social and political conflict (Gutmann 1999). From this point of view, philosophy, civic and science teachers can be regarded as epistemic agents, able to evaluate beliefs (own or other's) and to rationally sustain or change them. They should also be prepared to educate their students to attain the same abilities and dispositions.

There are no shared criteria in philosophy (including ethics) to identify universal problems or methods (since Plato and the Sophists to the twentieth-century analytic–continental divide) and no reaching a satisfyingly wide and stable consensus (Rabossi 2008; Rescher 1985). Value-laden questions are common in the social sciences and the humanities, and explicitly explored and addressed in philosophy education. Philosophy and civics education entail teaching and learning to pose questions, to analyse potential answers and to make decisions and act responsibly upon them. Students who encounter philosophy for the first time frequently have difficulties in dealing, intellectually and emotionally, with the mix of lively debate; rigorous, sophisticated reasoning; and the impossibility of reaching a sole, commonly accepted answer, typical of the philosophical outlook.

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[28] See also Ratcliffe and Grace (2003) (pp. 21–24 & pp. 29–32) for related questions in environmental education.

Since one or more philosophy courses (including ethics) have long been mandatory in the French, German, Italian, Spanish and most South and Central America curricula, a rich corpus of research and scholarship has been growing on philosophy education in the last few decades.[29] In particular, relevant work is taking place on topics such as how to teach and learn to ask philosophical questions and the art of posing relevant problems. Just as science education research has shown students (and even teachers) to display a tendency to "black or white" positions, from a naïvely realistic and dogmatic view of science to a (equally naïve) relativism or scepticism, a similar phenomenon has also been reported with regard to ethics teaching and learning (Allchin 1999; Paris 1994). Naïve dogmatic students display an unjustified belief in rules or principles learned from their family, friends, school, church or the media. They may be reinforced by teachers who adopt some normative ethical stance (say, Kantianism or rule utilitarianism) and present it as the best (or even the only) one. Crude relativistic students tend to regard everything as a matter of taste or opinion and lack any form of justification beyond personal likes or dislikes. Consideration of these issues is usually part of the training and practice of philosophy teachers. Research from the Philosophy for Children programme and from subsequent investigation in the field (UNESCO 2007; Kohan 2005) can offer interesting approaches to ethics education in primary and secondary education classrooms.[30] In science classes, tendencies to dogmatism could lead to a simple presentation of the "right" values in science (usually epistemic ones) coupled with a hagiographic (Adúriz-Bravo and Izquierdo-Aymerich 2005) view of scientists. On the other hand, presenting the class with a variety of ethical stances may lead them to an increasingly relativistic picture of ethics, wherein anything may be acceptable so long as the right ethical theory that supports a particular position may be found.

Value issues in science education share philosophical traits such as their intrinsic controversial nature, the lack of a single or even a more or less commonly accepted framework for analysis, the complexity of the discussions and the inexistence of a simple answer or commonly accepted conclusion for debates. This makes their teaching a particularly promising ground for the interaction and communication of different curriculum subjects that are usually kept apart. This interaction will be more fruitful on those occasions when science teachers adopt a controversial issue perspective rather than a descriptive one (Kolstø 2008). Different standpoints

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[29] See *Diotime* (on-line magazine on the teaching of philosophy, in French) and *Paideia* (the magazine of the Spanish Association of Philosophy Teachers). In English, *Teaching Philosophy* devoted to the discussion of the teaching and learning of philosophy since 1975. Also the American Philosophical Association publishes an on-line *Newsletter on Teaching Philosophy*. UNESCO (2007) has put together a comprehensive study of the status of the teaching of philosophy in the world. Recently a new series of regional documents expanding on the data presented in the 2007 study have been published. http://unesdoc.unesco.org.

[30] See Kasachkoff (2005) for an example of how a class of ethics may proceed. Items in the APA *Newsletter on Teaching Philosophy* (free on-line access) outline other approaches to ethics teaching. For a perspective on moral education from a theory of care point of view, see Noddings and Slote (2003).

regarding specific moral and ethical vocabulary and problems, such as freedom, responsibility, diverse theories on moral good, duty and rights that are frequently attended to and discussed in philosophy classrooms, can be reviewed and engaged with in science classrooms.[31] For instance, Conner (2010) presents and comments on several approaches to bioethics education: values clarification and values analysis; individual or collaborative inquiry approaches; futures thinking models. Ratcliffe and Grace (2003) discuss several structured learning strategies for whole-class and small-group discussion.

A significant consideration of ethical issues also entails core skills in reasoning, dialogue and argumentation. Value issues in science education are both dependent on and can contribute to developing these abilities.[32] When debating values-related issues, students should have the opportunity to consider the different, and sometimes conflicting, reasons there might be for accepting or opposing a position. And they should be able to foster the abilities to reason soundly about them and evaluate others' reasoning. But argumentation on its own is not enough to ensure the development of good ethical thinking. Reiss (2010) argues for three complementary criteria: first, the arguments must be reasonable. This does not mean that they must exclusively answer to the formal (classical) deductive logic validity criteria. Rational revision and change of beliefs imply the capability of logically, pragmatically and rhetorically producing and evaluating arguments, that is, the knowledge and correct application of both formal (validity) and non formal (acceptable, relevant and sufficient) criteria (Govier 2010). Sound arguing also requires a good understanding of the meaning of the terms employed and of whether the premises are warranted.[33]

In social, ethical and political issues, the premises may originate in natural, social or philosophical theories, making communication across the disciplines not only possible but highly desirable. A working understanding of ethical frameworks that have been developed throughout the history of philosophy is a fundamental help in avoiding those naïve extremes sketched above or mere common sense exchanges. There is no unique, universally accepted set of moral values, and in most multicultural societies there is only a partially shared set of commonly accepted values. But there are moral traditions (religious or otherwise) and philosophical theories that can give a framework to moral reasoning. So, in the second place, moral argumentation should be placed within an established, explicit ethical structure. Virtue ethics (whether of an Aristotelian persuasion or not), consequentialism (for instance, utilitarianism), deontological theories (Kantianism) and other philosophical frameworks may provide teachers and students with sophisticated arguments and examples to support discussions on ethical issues in scientific activity and scientific outcomes. An additional question is whether moral reasoning can be independent from an ethical theory: Aristotle's way of reasoning may be thought of

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[31] See Forge (1998, 2008) for a discussion of the issue of responsibility with regard to scientists and science practice.

[32] Zeidler (2003), Simmoneaux (2008), Zeidler and Sadler (2008), and Zohar (2008)

[33] Adúriz-Bravo and Revel Chion (2005), Adúriz-Bravo (2014), contributions to Erduran and Jiménez Aleixandre (2008), and Matthews (2009b)

as quite different from Kant's categorical imperative (Reiss 2010). Reiss outlines another issue worth exploring: the need to widen the moral community. He mentions two instances: interspecific ethics (Do animals have rights? Should those rights be taken into consideration, for instance, in experimentation with animals? (Rollin 2009; Lindahl 2010)); and intergenerational ethics (consequences for those far away in the geographical or in the historical sense, climate altered for generations, nuclear disposals). Lastly, conclusions must be arrived at as the outcome of genuine debate. Also, and this point would probably be contested by other philosophy educators, discussions should aim at consensus. Consensus should be understood as being coherent with one of the well-established traditions of ethical reasoning. At the same time, it cannot be permanent, but provisional, subject to discussion and change. Finally, Reiss emphasises that consensus should not be equated with a majority vote, since minority rights and interests and those of other interested parts without a voice (children, non-humans, the mentally infirm) ought to be taken into consideration.

Moral development of students is another relevant issue (Reiss 2010; Zeidler and Keefer 2003). Piaget (1948) presented his studies on the moral development of children in *The Moral Judgment of the Child*, based on how children viewed and responded to rules in the games they played. Later, Kohlberg developed Piaget's conclusions by conducting a series of interviews that included the discussion of several dilemmas (Kohlberg 1992; Kohlberg and Gilligan 1971). From the results of that research, he described three levels of development of moral judgment (preconventional, conventional and postconventional), each of them subdivided into two stages. The topmost stage presumed the notion of justice as a universal regulative principle, and the acceptance of universal, unconditioned ethical principles (akin to Kant's ethical theory). Therefore, his results should be considered as culture independent. Kohlberg's standpoint presupposed cognitive development, since changes in moral outlooks should be not only explicit but explained and justified by the individual. The passage from one stage to the other implied *learning*, in the sense of reconstructing and enriching the level below as a consequence of facing a dilemma that could not be solved satisfactorily. In the 1980s one of his disciples, Carol Gilligan (2003), criticised Kohlberg studies, indicating that all of the participants in them had been male. She proposed a new account that considered gender differences: a principle of justice on one side and a principle of caring on the other "voice" (as Gilligan called it) that constituted an acceptable basis for moral judgment. Caring implies a more contextualised point of view, different from the decontextualised, universal stance of Kant's deontological ethics. From a philosophical point of view, though, Kohlberg's project (and in this sense, Gilligan's too) should be reviewed. The idea of "development" implies a normative stance on morality, i.e. an ethical standpoint. It would be incorrect to assume simply that a Kantian conception of ethics could replace an Aristotelian or utilitarist outlook, or *vice versa*. Also, in each of the stages Kohlberg describes, morally responsible behaviour can coexist with a less responsible one, whether the underlying rationale corresponds to the Golden Rule or to a utilitarian analysis of consequences. Reiss (2010) suggests a set of indicators of progression in ethical reasoning that may be a useful tool for teachers in designing strategies that would help students move from a lower level of ethical thinking to a higher point. This set, though akin to Kohlberg stages, refers to different perspectives on normative ethics. Although it could be revisable from different philosophical and ethical points of view, it represents an interesting starting point for teachers to consider the sense of the progress they want to help their students achieve.

But it can be argued that in-depth teaching of ethics theories and moral reasoning cannot be the object of a natural science course: teachers will probably not have the time nor the specific knowledge or abilities to embark on it. A reasonable discussion of these theories would be impracticable, turning the science classroom into a course on normative ethics (Crosthwaite 2001). And other subjects in the curriculum, in the humanities or the social sciences, will probably find it more congenial and specific. Here again, the dilemma becomes less pressing in those educational systems that include a philosophy course in its own right. But, at the same time, natural, social sciences and philosophy teachers should have enough familiarity with their mutual frameworks to be able to orientate moral reasoning, and, where possible, open up fruitful collaboration between subjects or departments in schools. This does not mean ignoring that in most countries a discipline-based curriculum poses obstacles to cross-curricular cooperation. Although teacher education may not be a sufficient condition towards changing this situation, it may be thought of as a necessary one.

33.7 Conclusion

Science education does not need to encompass all aspects of education. Certainly, not every NOS issue may be fully addressed without running the risk of turning science classrooms into philosophy, history or sociology ones. Machamer and Douglas (1999, p. 53) put it nicely:

> We realize that no one can do this all the time, or else science would never get done. But to know how to do so, and that the possibility always exists for questioning the data, the reasons and the goals – this is what philosophy of science can teach, and what the history of science demonstrates is necessary.

On the other hand, philosophy teachers will address ethical or political problems from a different point of view. They would rightfully not feel constrained by the need to exclude perspectives that clash with the scientific worldview. So, there will probably be divergences with the aims and strategies of science education.

However, philosophy and science teachers, as all teachers, are educators in the broader sense of the term. As such, they need a wide knowledge of scientific, ethical and political issues, values and practices that would allow them to be critically aware and to avoid inadvertently conveying an unconsidered stance (a hidden curriculum), and here collaboration between science and philosophy education may have a fundamental role to play.

Also, this familiarity may enable teachers to respond to students' emergent or spontaneous questions in class and facilitate the interaction between colleagues from different disciplines in designing joint school projects which would benefit from a mutual acquaintance with each other's outlooks, values and languages. Active engagement in reflecting on standing practices and designing and implementing new ones seem to be particularly relevant to an adequate understanding of social, political and ethical issues in science knowledge and practices. Practising teachers may therefore find that these issues can be integrated in their own ongoing teaching strategies and, hopefully, act upon it.

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Chapter 34
Social Studies of Science and Science Teaching

Gábor Kutrovátz and Gábor Áron Zemplén

Sagredo: As educators of science, we face fundamental problems like what kind of science we ought to teach in schools, how much, in what manner, and for what purposes. In the past decades, these questions have received increasing scholarly attention, and the enormous complexity of the field of relevant issues and approaches has been broadly recognized (McComas 2000). "Nature of science" has been identified as a core problem: how the teaching *of* science is, or should be, related to, supported by, and reconciled with teaching *about* science. In other words, science education is now believed to serve several purposes, and providing students with scientific knowledge is only one of them. Another purpose is to convey a general understanding of science, the scientific method, the reliability of scientific knowledge, and how and in what form it is accessible and useful to nonscientists and what social, cultural, or educational roles science can and does have. These questions have been raised in various fields. Philosophers of science have been investigating the most general problems concerning scientific enterprise for at least a century now, and historians of science have their own, equally important and partly overlapping, tradition of studying the dynamics of science (Holton 2003; Machamer 1998). But what about sociology? Various views and approaches, together with their merits and drawbacks, limitations, and contexts, need to be studied to find out for ourselves what we, educators, can best learn from them. Here is my suggestion for today: let us have a look at some of the most important views and approaches within the social studies

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of science and submit them to the scrutiny of our discussion.[1] After all, we are all familiar with the pedagogical values of presenting ideas in dialogue form.

Simplicio: I see no reason why "philosophy" can't be replaced by "sociology" or "social studies" in a favorite quote of mine. According to Feynman, "philosophy of science is about as useful to scientists as ornithology is to birds" (Kitcher 1998, p. 32). Do you really think that "hard" sciences can be meaningfully analyzed with the toolkit of "soft" social sciences, having a far less secure methodological base than their subject? Should we teach "xxx studies" in the little time allotted to the "science of xxx"?

Salviati: "Most scientists tend to understand little more about science than fish *about* hydrodynamics," as the philosopher Imre Lakatos (1970, p. 148n) offered another concise judgment. That's a shame, as there are a number of things "about science" (Barnes 1985) that would-be scientists can find very important to learn in school. When they enter the scientific field, they are often unprepared to cope with what they encounter and what they did not learn from studying scientific theories. Moreover, not every student of science will become a scientist, and those who will not may find philosophical perspectives as useful as sociological ones. All in all, science seems to be similar to other aspects of human society.

Simplicio: Similar? Science is special exactly because it is dissimilar. In what relevant way would it be similar?

Sagredo: For example, power is concentrated in the hands of a small minority, just like in most areas of human activity. Sociological studies have revealed serious inequalities in science, an enterprise that seems, to many, to represent democratic values. A vast majority of all publications is written by a small minority of all scientists (Lotka 1926). And it is not only that some scientists try to publish more simply because they are more prolific, but the more credit one gets, the easier it is to publish. Moreover, publication forums also receive unbalanced attention: from the 30,000 scientific journals of the 1960s, approximately 170 were the most prestigious, and half of all the interest in libraries was focused on this tiny proportion of the entire body of journals (Price 1986, p. 67). Similar inequalities were identified in citation patterns: while, on average, every scientific paper is cited only once by later publications, in reality, most papers will never get cited later, which leaves us with a few influential and highly visible papers that others read, surrounded by a myriad of papers lost in collective ignorance (*ibid.* p. 73). Robert Merton, a founding father of the sociology of science, called this the Matthew effect (Merton 1968), based on a quote from the Bible: "For whosoever hath, to him shall be given, and he shall have more abundance: but whosoever hath not, from him shall be taken away even that he hath" (Matthew 13:12, King James Bible, Cambridge Ed.). Scientists learn to live with this distribution of power, but it may take them a long time to find

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out from bitter personal experience what they could have learnt already in school about the peculiar meritocracy of science.

Simplicio: I concur, every student should know a bit of sociology, probably about this much: if you look at science as an activity, you will see that it is an institutionalized subsystem or field of society, with its own rules to follow, values to respect, goals to pursue, norms to be governed by, etc. This activity is performed by a social group, that of scientists, which is structured both "vertically" in a hierarchical order, and through complex power relations, and "horizontally" according to disciplinary maps, national and geographical factors, to start with. Science relies on a number of different resources to comply with its primary function, i.e., the production of reliable knowledge, or empirically fruitful theories, theoretical and practical knowledge, or even legitimizing various democratic functions of the society, as Salviati may claim. Certain resources are "material" like sites of activity (institutes, universities, etc.), financial conditions (salaries, grants, scholarships), and other technical and instrumental resources. Others are "symbolic" like the structure of ranks, degrees, and honors or protocols of formal communication and publication and all kinds of norms and values as mentioned above. Sociology of science, as I see things, investigates precisely these things…

Sagredo:…and more. In the past few decades, all disciplines examining science have developed a growing sensitivity to insights coming from the social sciences. "Sociology of science," "sociology of (scientific) knowledge," "social studies of science and technology," and "science (and technology) studies" are promising labels referring to a complex array of research traditions investigating how the study of society and the study of science can inform and supplement one another.

Simplicio: Despite the field's popularity, it remains unclear to me from a science education perspective how relevant these approaches are and what lessons we can take home from consulting them. And here is my answer. If we introduce a distinction between the form of scientific activity and the content of scientific knowledge, I expect that sociologists have a lot to say about the first, but are wrong if they think they can teach us anything about the second. Sociology of science and sociology of knowledge are different enterprises. Proper sociologists of science restrict themselves to the study of the social dimensions of scientific activity, like the analysis of the Matthew effect, and this is what I find promising about sociology. On the other hand, sociology of knowledge addresses the problem on how social factors affect what and in what way a certain culture thinks about the world – their conceptual categories, systems of classification, and so on. I believe that this is where sociology is *not* able to examine science meaningfully. Even prominent figures of this field admitted that when it comes to scientific knowledge, these external factors cease to matter and the "sociology of knowledge" perspective loses all power (Mannheim 1936, p. 239, as interpreted by Bloor 1973).

Salviati: An outdated and narrow view, as I hope to show later. But supposing for a second that you are right, what are the "social dimensions of scientific activity" that sociologists can legitimately study?

Simplicio: Sociologists of science provided a number of statistical analyses of the institutional patterns of science. Investigations, similar to those of Merton, were carried out from the 1960s and 1970s by Harriet Zuckerman, Jonathan Cole, Stephen Cole, Joseph Ben-David, Derek J. de Solla Price, and many others. I would be very surprised if you told me that this quantitative trend, opening a perspective on a measurable science, is uninteresting or irrelevant to students who need to understand what science is.

Sagredo: True. For example, Merton's study of publication patterns included the analysis of rejection rates for the publication of manuscripts in various academic journals. By comparing these rejection rates in different academic fields he found that, perhaps contrary to our prior intuition, journals in the arts, humanities, and social sciences are more strict than journals in the natural sciences. While an average of 90 % of the manuscripts were rejected by the most important history journals considered by Merton in 1967 (closely followed by literature, philosophy, political science, and sociology journals), only 20–30 % of manuscripts were rejected in biological, physical, and geological journals (Zuckermann and Merton 1971). How interesting, as if candidates for publication found it far easier to comply with the publication standards of scientific fields than those within the humanities….

Salviati: This is a red herring… Surely, these isolated sets of data can be interpreted in many different ways (Hess 1997, pp. 65–66), and I am afraid it is too rash to jump to unjustified conclusions concerning the strictness of publication standards. I can readily offer other explanations for the phenomenon. Consider, for instance, a different statistical tool, introduced by another prominent sociologist of science, Derek de Solla Price (1986, pp. 166–179). The so-called Price Index tells us the proportion of those publications, cited by a scientific journal of field or discipline, that are not older than 5 years, relative to the number of all citations. What he found in the 1960s (and this hasn't changed significantly since his time) is that the proportion is 60–70 % for hard sciences like physics, while only 20 % for philosophy. What this means is that in hard sciences, the immediate knowledge base that researchers rely on is far more up-to-date and recent than in softer fields. In my opinion, this fact discourages amateurs (i.e., alleged contributors with insufficient professional background) from submitting their pet theories to science journals, seeing how unable they are to participate in the technical discussion. Self-made academics in the humanities, on the other hand, may believe that rules are less esoteric and therefore the boundaries of scholarly discourse seem less strict, and they try to put their voices in – just to find themselves rejected as well in the end….

Simplicio: I loathe to interrupt, dear Salviati, but do not forget the serious methodological problems inherent in social sciences. As opposed to the natural sciences, social sciences have not yet crystallized their sound methodological foundations, and high rejection rates of publication, as well as intensive use of older technical literature, stand witness to this methodological uncertainty. Around the beginning of the twentieth century, a number of authors argued for a fundamental methodological difference between the natural sciences on the one hand and humanities and social sciences on the other. Others believed that there is some kind of unity to all the sciences, and an overarching methodology unites all scientific enterprises. This *Methodenstreit* lasted at least three generations…

Sagredo: … and participants were lost in an ocean of complicated problems. I wouldn't be happy to lose the focus of our discussion. Both of you made a point though. Simplicio is right when urging the importance of statistical, quantitative findings about science: they largely contribute to our complex understanding of the phenomenon. But Salviati was also right when he pointed out that statistics can be very misleading without sufficient care and precaution.

Salviati: It is a general problem that statistics leaves us in partial darkness about the significance of the data. For example, sticking to publication patterns, the numbers show that when scientists become referees of their peers' papers, the younger referees are usually more strict (and more likely to reject) than older colleagues. Similarly with respect to rank, researchers with higher ranks are more admissive of manuscripts than those of lower ranks (Zuckermann and Merton 1971). Now this is all fascinating, but what does it mean? Not even those publishing these statistics seem to know the precise reasons and underlying mechanisms. What do we gain if we teach such things to students who need to understand what science is?

Simplicio: As Salviati noticed, teaching nature of science (NOS) includes teaching the would-be scientists, the academic *Nachwuchs*, and if you think of performance assessment, the study of publication patterns has obvious advantages that we already utilize in our everyday scientific activity. If you want to assess scientific performance, the most obvious way is to look at individual researchers: how many papers and in what journals did they publish.

Sagredo: "Scientometrics," as they often call this field (and also one of its flagship journals), aims to measure scientific output by counting and ranking publications, calculating impact factors and other indicators. While it has its roots in quantitative sociology of science, by today it has become an independent field that we often find indispensable… even though indicators for institutions are more reliable than any measurement tool that compares individual researchers…. It is a tool that we frequently rely on when it comes to assessment, despite some fundamental problems like the gradual shift from descriptive measurement of scientific productivity to a normative prescription of what counts as scientific productivity. The numerous difficulties would boil our discussion down to nitty-gritty details, so let us declare that quantitative sociology of science and the study of scientific institutions have some clear lessons to teach….

Salviati: Like in the case of the Matthew effect, one of the things I tend to emphasize about science is that it is a human enterprise, with all the typical features and "imperfections" all human enterprises have in common. Power inequalities are part and parcel of any human activity, and science is no exception. It is a simple game of power with winners and losers.

Sagredo: Such a profane claim would do injustice to Merton who did more than studying statistics. Above all, he sought to identify what distinguishes science from other things that humans do. He found that it is a peculiar set of norms that govern scientific activity, amounting to a "scientific ethos" (Merton 1942). There are four elements to this. Universalism means that the acceptance or rejection of theories is an impersonal process, where the origin of the scientist making the claim (e.g., class, gender, ethnical identity) is irrelevant to the acceptability of the claim. Communalism (or communism) means that knowledge is the intellectual property of the community, and every member has equal right to access it, contribute to it, or criticize it. Disinterestedness means that the assessment of scientific claims should be kept independent of the local interests and biases of certain groups. Finally, organized skepticism means that all scientific claims must be submitted to the scrutiny of critical thinking, and no dogmas should be considered as beyond skepticism.

Salviati: I have to admit that I find these expectations entertaining, given the mentioned profound power inequalities in science. Can we really expect scientists to have no personal interests, ready to share their most cherished results with everyone, and eager to criticize even the most central beliefs of their disciplines? Do we get closer to what science is if we teach this utopistic vision? Or do we believe that scientific education should include some training in ethics to implant these noble norms in students?

Simplicio: Salviati, I am never sure whether you are ironic or simply ignorant. Merton's norms of scientific ethos have puzzled many authors, but it is clear from the original texts that Merton did not intend to present these as "personality traits" of actual or ideal scientists. On the contrary, Mertonian norms do not hold at the level of individuals, and they are certainly not meant as behavioral prescriptions. Scientists are humans; their local interests, biases, dogmas, and secrets of the trade motivate individual scientists in doing what they do and inform them how to do it. So Merton's norms are general and symbolic value orientations that, at the collective level, govern the formation of rules and behavioral patterns in such a way that the final result of the entire activity, i.e., scientific knowledge, will accord to these general expectations.

Salviati: And how does this happen? Through some "cunning of reason"– out of the sum of individual selfishness and social contingency, something emerges that can be seen as pure and disinterested knowledge serving the ends of humankind.

Sagredo: And indeed, something like that does happen. The conditions of the "miracle" are embedded in the institutional patterns of scientific activity. It is precisely by studying these patterns that we can tell how individual interests, biases, commitments, and contingencies can result, through an institutionalized collective cognitive process, in a beneficial advancement of global science and human knowledge. And this is one of the most important reasons why a scientific approach to the workings of science is essential today.

Salviati: Fair words. Still, I feel uneasy about overemphasizing the statistical study of institutions when addressing the question of what science is. First, science may be seen very differently from the perspectives of other metascientific approaches: while it is a system of organized action for sociologists, it is also a body of texts and instruments for historians, or a world of abstract propositions and their logical relations to philosophers, to mention just a few views. In order to grasp science, all these perspectives should be taken into account simultaneously. Science, for example, may be seen as an institutionalized social field in modern times, but before the nineteenth century, the general institutional structure was very different, and before the seventeenth century, there was nothing similar to what science seems to be from the perspective you described. Yet most histories of science will go back to far earlier times. Would you tell your students that Euclid didn't do mathematics, or Ptolemy astronomy, just because science – as the sociologists describe it – did not exist in premodern times?

Sagredo: You are provoking us again. To say that institutionalized social action is a fundamental aspect of what we mean by the term "science" is not to claim that it is all there is to science. But the point you've just made is important: science is not something static and unchanging. The development, or to use a more neutral term, the dynamics of science does not only consist in ever better theories or more precise and comprehensive knowledge, whatever these mean (see the chapters on philosophy). On the contrary, the real dynamics of science can be revealed only by addressing its social and cultural conditions. For example, when Merton sought to identify the norms of scientific ethos, his real question was, in what social circumstances do we find a wholesome scientific activity? He believed that the Nazi Germany or the Soviet Union did not provide ideal conditions for doing science, since some norms were not respected. The norm of universality is clearly violated when ethnic and cultural circumstances of the proponents influence the reception of ideas. Merton's fundamental question was to find the norms that can provide the most ideal circumstances for scientific development when implemented in institutional practice (Merton 1938a).

Simplicio: From early on, Merton's work was imbued with a historical perspective. In his doctoral thesis, he investigated how modern science was formed in seventeenth- and eighteenth-century England. His central claim was that Protestant ethics based on Puritan principles proved beneficial for the development of "natural philosophy" (Merton 1938b). The two basic tenets of this philosophy were doing things for the glory of God and for the utility of mankind. Merton quoted many passages from prominent scientists of the era to show how these principles lead to the intellectual pursuit we call science, being both rationalist (by seeking a theoretical understanding of the Creation, i.e., nature) and empiricist (by submitting this understanding to the special needs and purposes of humans). He also relied on statistical analyses to establish the connection between scientific performance and social institutions and found both that Protestants were overrepresented in scientific societies (like the Royal Society) and that novel scientific views and results found their way to Protestant school curricula faster than to Catholic ones.

Sagredo: And this is just part of the story. The "utility of mankind" aspect is clearly visible if you look at the practical problems that early scientists of the era sought to solve. As England's power was largely dependent on sailing the seas, it comes hardly as a surprise that scientists addressed problems relevant for sailing: they studied astronomy in order to improve navigation and determine the position of the ships; they studied the motion of the pendulum to build better clocks, as precise timekeeping appeared to be essential for the determination of longitude; and they studied hydrostatics to build ever larger and faster ships. Mining, another vital area behind industrial growth, was laden with problems that could be addressed by hydrostatics and aerostatics, like circulating water and the air in mines. And, of course, the power, efficiency, and accuracy of guns and cannons raised many questions related to projectile paths, the compression and explosion of gases, rigidity and constancy of metals, etc. – all popular research areas of the time.

Salviati: All this seems to indicate that the direction of scientific research is a function of society. Soviet historians, most prominently Boris Hessen (2009), held similar views already in 1931. They pinpointed the role of military and information technologies during the scientific revolution and claimed that all important results of the era were rooted in practical questions. But even if their findings were similar to that of Merton, their starting point was different. Hessen and his colleagues worked in a framework that Merton later found inadequate for the purposes of science.

Simplicio: They dogmatically followed the Marxist ideological assumption that it is modes of production in the material world that determine the “superstructure,” i.e., the conditions of social, political, and intellectual processes. From their point of view, the interconnectedness of scientific research and social conditions is anything but surprising. But if you want to understand the real dynamics of science, you had better consult statistics. Did you know that the total population of scientists is growing more rapidly than the population of nonscientists? This tendency was recognized by Derek de Solla Price in 1963 (Price 1986), who claimed that science (number of scientists, journals, papers, institutes, etc.) had been growing exponentially since the end of the seventeenth century when modern science had been created. Most indicators of the size of science double in a period of approximately 15 years, and that means that, on average, science becomes 1,000 times more populous in a span of 150 years. Merton also realized that in the modern societies of his time, the age distribution of researchers is different from that of the entire population: in science younger age groups are overrepresented.

Sagredo: Surely this has profound consequences for our understanding of how science works. It is always in the present: taking any moment in time, about half the scientists of the history have worked in the past 15 years, so an old scientist having worked 45 years can say that he or she has been contemporary to more than 90 % of all the scientists who have ever lived so far. This may tell us why, in most research areas, the Price Index is so high: recent science is not only more developed, but is also far more detailed and populous, than past science. This inevitably leads to increasing specification, since a research area becomes too large to handle when the number of experts exceeds a practical limit, so new research areas split from others to make room for an ever-growing number of newcomers.

Salviati: And how long can this miracle last? If the ratio of scientists increases in modern societies, there must come a time when everybody becomes a scientist. True that human population is growing in a more or less exponential manner, but the doubling rate is closer to 30 years than 15, so scientists will have to fill up the future. Fine with me, but who will work then?

Sagredo: Price asked the same question. Surely, such a growth must cease before every single person becomes a scientist. Practically, science is becoming simply too expensive to be paid by the rest of society. By analyzing the growth curves, Price came to realize that the growth was about to end soon, in his lifetime. After that, science needs to transform radically in order to survive….

Salviati: So you are talking about what Nowotny et al. (2001) called Mode 2 science. They realized that the social context of science was changing in a way that favors multidisciplinary projects focused on specific real-world problems, while traditional long-term theoretical research confined within certain disciplines ("Mode 1 science") was losing its former ground. According to this view, contemporary scientists are problem-solvers in the context of technological, social, and everyday needs. Is that your solution?

Sagredo: Exactly. Or, to use another term, John Ziman (2000) coined "post-academic" science to describe how academic science, funded more or less independently by the state in order to conduct free research, is gradually replaced with a research culture that is supported by multinational industrial or corporate actors for dealing with well-defined and context-given problems. If the state can no longer quench the ever-growing appetite of science, researchers have to find other forms of support. This looks inevitable, but the consequences are as yet far from clear. It seems probable that the role of "basic research" (a free pursuit of knowledge) will be reduced radically, while "applied research" (seeking a solution to a specific given problem) will dominate science. Moreover, the primary social function of science is no longer providing knowledge of how the world is, but finding answers to "external" questions, given to researchers by whoever pays them. All this affects the institutional structure of science, since the primary sites of research are less and less the state-funded research institutes or the universities… Students who are considering a career in science would clearly find these trends essential in terms of their career choices.

Simplicio: And as the institutional structure is transforming, so are the norms themselves that guide behavior in science. Ziman (2000) argues that Merton's norms are becoming obsolete. Knowledge is not universal any more, since scientific answers are strongly influenced by the circumstances of production. Results are increasingly unavailable in a free and public way to other members of the community, as they are the property of the patentee. Science is obviously far from being disinterested, for research serves the immediate interests of the sponsor. Finally, there is no time for organized skepticism in a world of deadlines and short-term projects: a firm result is expected by the end of the given period of research. If Merton's norms describe an ideal state in which traditional science can proliferate, Ziman opens our eyes to a different and more mundane reality.

Salviati: I see no reason for despair. In my understanding, science is adapting to a changing social environment. The dynamics of science is analogous to biological evolution, to invoke another classic from the social studies of science (Thomas S. Kuhn 1970, pp. 171–173, 2000a, pp. 96–99). The evolution of a complex system of theories and paradigms is not a linear progress aimed at some desirable end like "truth" or "ever better theories"….

Simplicio: Are you sure that the science/evolution metaphor implies the lack of a final truth? You say that "paradigms" (a term that is used in radically different senses throughout Kuhn's main work; see Masterman 1970) are like biological species adapting to a changing environment. Yet biological evolution produced us, humans, and while other species are adapted to different specific environments, human culture is a universal solution to an unlimited range of environments. So, why rule out that science is a similarly successful, potentially universal epistemic tool…?

Salviati: … one that threatens us with a general epistemic and social collapse, just like human behavior may easily trigger a global ecological catastrophe?

Sagredo: Before science can look back on as long an evolutionary path as nature can boast with, let us suppose that the process is driven by the past failures, rather than drawn toward a goal. What Salviati's Kuhn implies to me is this: there is no need to look for an "essence" of science, like Merton's norms or methodological rules prescribed by philosophers. Science is an ever-changing enterprise, and turning our attention to its past development opens a perspective that is at least as informative as the quantitative study of its present form.

Salviati: And this approach is more profoundly historical than Merton's analysis of the seventeenth century or Price's statistics about growth.

Simplicio: Let me ask this: if we dispense with the idea that science has an "essence" or, to put it less loftily, it has some constant and unchanging core of commitments and orientations, then what are we left with to teach as "nature of science"? Can we avoid discussing Salviati's post-Kuhnian relativists at this point (see also the special issue Matthews 1997)?

Salviati: These "relativists" or, more precisely, constructivists have provided us with the most detailed case studies of science in action, how good (or bad) science is actually done. Didactic transposition of any one of these detailed case studies can give a glimpse of the whole of science, instead of focusing on declarative statements (Allchin 2003).

Sagredo: Overemphasizing one perspective can be as deceptive as sticking to another. Still, I find Kuhn's emphasis on differences insightful. If we want to understand what science is, we need to look at it in various times and cultures and to identify the contingencies that help us see better behind the contingent and ephemeral.

Simplicio: Everything seems to be contingent for Kuhn in my reading. Salviati was proud to drop in the term "paradigm," as if the popularity of a term would do justice to its adequacy. But in Kuhn's view, paradigms come and go, they replace one another, and their relation is described by him as "incommensurable" (Kuhn 1970). He argues that there is no rational stance from where we could tell that the new paradigm is better than the old, and thus overall progress disappears from science. Would you tell your students that Copernican theory of planetary motions is just as good as the Ptolemaic system, since there are no universal standards to compare them? As an educator, I strongly protest!

Sagredo: Kuhn is a tad more complex than that, as it is not theories he holds incommensurable but, as you say, paradigms. Paradigms are not theories and sets of propositions about the world, although they contain theories and propositions. They also involve more basic elements such as rules and methods to conduct inquiry, successful solutions that serve as models for solving future problems, and ontological commitments about the entities our explanations rely on that help us interpret phenomena. In short, paradigms are ways to see the natural world. Of course, we do not want to teach our students to see the world as the ancient Greeks did, and we can argue efficiently that the Copernican theory is better than the Ptolemaic, just as Newton's theory of motion is better than that of Aristotle. But it is important for us to bear in mind that these "theories" as we present them are interpreted in our paradigm, relying on our own questions and evaluation criteria, and our judgments are guided by our own interests and predispositions.

Salviati: Exactly. And I believe that this radically historical perspective may help students to see science from a healthy distance, by contextualizing those elements of modern science that they otherwise would see as evident. Take Newtonian physics as an example. In order to show its merits, we present to them the very same solutions that made the Newtonians so successful: we talk about swinging pendulums, colliding balls, the elongation of springs, or the motion of planets – and lo and behold, these are phenomena where Newton's theory provides simple and efficient explanations, so Newton was correct! But are pendulums, colliding balls, springs, and planets important to an average student? We implicitly suggest that the key to understanding the physical world is by addressing these phenomena, and many find this kind of physics irrelevant and boring. If we teach any history of science before the early modern period, we simply say that Aristotle's physics was obviously naïve and dull, but we do not tell students that the phenomena that the Aristotelians wanted to explain, and the criteria of what counts as successful explanation, were radically different then. My point is, if we told them about these differences, they would better understand what modern physics is good for (for a general appraisal, see Matthews 2000, 2004)…

Simplicio: …and we would have even less time left to teach them proper modern science. After all, Aristotle lived a long, long time ago, and I don't see why he would be of any interest to us if you are correct in claiming that his world was radically different. I don't believe in radical raptures, and I can't accept that every new paradigm starts everything completely anew. Otherwise, how could we learn from the past if there is nothing in common between him and us? The concept of incommensurability is highly questionable….

Sagredo: The concept has drawn similar reactions from many scholars, and Kuhn seems to have softened his views. The emergence of new paradigms is analogous to speciation in evolution, and this evolutionary metaphor became more prominent in his later writings. The gap between paradigms is radical, but "lexicons" of research communities can be translated, by learning the conceptual system guiding their world view. Communication between lexicons is possible (Kuhn 2000b).

Simplicio: And this is where I firmly protest. When Kuhn claims that general conceptual structures orient our scientific theories, he simply ignores that science is an enterprise that, by studying nature and nothing else, helps us get rid of specific social conditions and contingencies. Remember the distinction I made between the meaningful study of institutional structures and the misguided sociological analysis of the contents of scientific knowledge? While Kuhn was not a sociologist, his views prompted many tenets in what is called post-Kuhnian science studies, and I think these tenets were a change for the worse.

Sagredo: You probably think of the most explicit and most influential theoretical backing to post-Kuhnian science studies developed by the Edinburgh School including David Bloor, Barry Barnes, John Henry, and others. They launched what is called the Strong Program in the sociology of scientific knowledge (SSK), characterized by four planks: (1) causality, it is "concerned with the conditions which bring about belief, or states of knowledge"; (2) impartiality, "it would be impartial with respect to truth and falsity, rationality or irrationality, success or failure"; (3) symmetry, "the same types of cause would explain, say, true and false beliefs"; and (4) reflexivity, "its patterns of explanation would have to be applicable to sociology itself" (Bloor 1992, p. 7). The main project of the program was to construct the theoretical underpinning of a scientific understanding of science…

Salviati: … and let us add that they seem to have failed in that, since most subsequent authors in the field of science studies disputed several central points in the theoretical core of SSK. Still, and more importantly, SSK motivated many basic trends in the social studies of science. Versions of this program were employed in studies of scientific laboratory work (Knorr-Cetina 1981; Latour and Woolgar 1979), analyses of scientific controversies (Collins and Pinch 1982), histories of older (Shapin and Schaffer 1985) and recent (Pickering 1984) science, theories of technology (Bijker et al. 1987), etc. They all acknowledge their debts to SSK.

Simplicio: Relativists! I find it hard to keep calm when I meet their views. The people you mentioned might be simply wrong but benevolent, but they encouraged a hoard of hostile intellectuals – think of the various postmodernist, post-structuralist, neo-Marxist, feminist, environmentalist, etc., criticisms of science. Remember the Science Wars! A great number of scientists and philosophers pointed out that (i) the SSK tenets and their intellectual offspring are simply wrong and (ii) these views give rise to a general social hostility toward science.

Salviati: But these charges are seriously mistaken, as the science studies authors attacked in the Science Wars clearly showed. But if you haven't read them, I am happy to accept your challenge right here and prove the validity of "relativist" approaches….

Sagredo: But that would lead us into philosophy and a dense discussion. Still, it is worth considering the main charge concerning why SSK is wrong, emphasized by Alan Sokal and Jean Bricmont (1998) in their sweeping criticism of relativist science studies. When studying scientific knowledge, sociologists tend to refer to all kinds of social and cultural factors when explaining why a certain community accepted specific beliefs, but they forget about nature and its causal responsibility for the beliefs we hold. Isn't it a strongly one-sided perspective? If we tell our students that scientific theories are caused by social factors, how can we encourage them to carry out empirical investigations and the study of nature itself?

Salviati: You've just committed a widespread mistake: you seem to read SSK inattentively. With regard to the first plank of SSK, Bloor and his colleagues stress that all beliefs have various causes, but not all of these causes are social (Bloor 1992, p. 7). Natural causes obviously play their role.

Simplicio: This sounds promising, yet does it not undermine the symmetry principle, since true beliefs surely have more natural causes and false beliefs must have more social causes? If sociologists examined all the causes prompting a belief, they would certainly realize that much (Slezak 1994a). So why don't they talk about natural causes?

Salviati: The reasons are manifold, and they vary from author to author. The simplest reason is that sociological research has no access to nature independently of natural science as the very object of its study, so "nature" appears only in beliefs about it. This is a purely methodological interpretation advocated, e.g., by Harry Collins, called "methodological relativism" (Collins 2001a, p. 184). David Bloor offers another methodological explanation when he claims that sociologists are interested only in the differences between rival theories, and since nature that researchers study is the same, it is the different social factors that result in different interpretations of the same thing (Bloor 1999, p. 93). But the same Bloor gives philosophical arguments too, similar to that of some constructivist authors such as Karin Knorr-Cetina (1993). According to this view, since nature's causal role (*an sich*) is entirely unspecified (and inaccessible independently of the beliefs we hold about it), everything we conceive is constituted by our prior beliefs and categories. Kuhn's epistemological perspective building on "lexicons" supports a similar tenet, no wonder that he saw himself as a Kantian with movable categories (Kuhn 2000a, p. 264). There are even more radical views like that of Bruno Latour who denies the distinction not only between nature and society but also between things and beliefs about them, at an ontological level (Latour 1993), or post-humanists like Andy Pickering who mix every possible cause in their narrative and call it the "mangle of practice" (Pickering 1995). These radical views come very handy when it comes to understanding and discussing atypical or Oriental science....

Simplicio: Please stop! This much has been more than enough to illustrate that there is no theoretical consensus within the social studies of science. Just think of the "epistemological chicken" debate between relativists, where the stake was who dares to come up with the more extreme epistemological position (Collins and

Yearly 1992), or the controversy between Bloor (1999) and Latour (1999) where, intimidated by the criticisms they received in the Science Wars, they reproached each other for adopting harmful philosophical views. This proves not only that relativists stand on highly problematic theoretical ground but also that teaching their theories to students would result in confusion and despair (Slezak 1994b and Chap. 31).

Salviati: Science studies are manifold, as the term "studies" indicates – and we haven't mentioned a number of approaches yet. But then, to return to an earlier problem we raised, do you really think that science is a single and unified entity? While the positivist illusion of unity was expressed by launching the ambitious *International Encyclopedia of Unified Science*, the planned 14 or 26 volumes (Morris 1960) never came out. The second and last volume ironically contained Kuhn's revolutionary book on revolutions (1970). Post-Kuhnian science studies authors argue for the disunity of science (Galison and Stump 1996), and constructivists like Knorr-Cetina (1999) view different scientific fields as disconnected epistemic cultures. And we can go further than simply acknowledging disunity: thanks to science studies, we now have conceptual tools to study boundary phenomena between and around scientific areas. Think of "boundary work" introduced by Merton's student Thomas Gieryn (1983, 1999) to describe the ideological and rhetorical efforts that draw and shift different boundaries. Or think of "boundary objects" (Star and Griesemer 1989), entities that connect various groups in the large networks of science, "boundary organizations" (Guston 1999), "boundary infrastructures" (Bowker and Star 1999), or the "trading zones" that emerge when groups with different enculturation do research together (Galison 1997)….

Simplicio: I can't think of so many things simultaneously, and I am repelled by this conceptual and methodological cacophony. But I can anticipate your point: if there is no such single entity as "science," but only networks of "sciences," then what are we left with to teach as "nature of science"? And here is my answer: everything we normally teach, perhaps supplemented with some insights from the sociology of scientific institutions. I simply cannot accept claims or conceptual tools from a field which is so heterogeneous that its representatives can't agree on how to start building a minimally common theoretical core.

Sagredo: Your favored sociology of scientific institutions was not free of fundamental divergences in theoretical and methodological questions – emerging fields usually aren't. I agree that introducing too many theoretical positions in science classes could prove less useful than harmful. Still, what unites these authors is not the theory but the general perspective and the resulting approach to science. As Salviati mentioned earlier, science can be seen as a set of human practices that are as contingent, political, interest-driven, opportunistic, and mundane as any other human enterprise.

Simplicio: And this is the second mistake of SSK I mentioned, and a very bitter one. Why do we do science? Because we believe that it is the most reliable cognitive enterprise we have, resulting in the most secure knowledge about the world. The question in this case is not how science is the same as other cultural fields, but how it is different, something more. If we teach our students anything "about science," the guiding question must be, what's so special about science (Bauer 2000)?

Sagredo: But then it is useful not to tell idealized half-truths about it. Those who become scientists will learn of the imperfections soon enough, but it may take them by surprise and make it difficult for them to adopt to the reality of actual practice, as opposed to the ideals they pursued when choosing this profession. And those who will not do science professionally may find, when confronted with science depicted in the media, that scientists are not the good guys in flawless white lab coats that popularizing efforts try to show, and they might get disappointed and disrespectful.

Salviati: Importantly, SSK-type relativists try to follow the most general scientific principles. Scientists explain phenomena by referring to causes, and sociologists of science do the same….

Simplicio: But they do not agree in what type of causes they use! Some of them explain the general with the general: for Marxists larger formations of knowledge (cognitive styles, conceptual schemes, paradigmatic theories, etc.) are explained with reference to broad social characteristics. Others explain particular knowledge claims with reference to general social settings. Here the particular cases to be explained can range from specific beliefs to small-scale theories, advocated by a particular scientist, and the general basis of explanation can comprise the norms within the wide community, or general interests of cognitive, economic, or political kind, or technological possibilities available at a wider sociohistorical level. In these cases the source of explanation expands far wider than the local topic and its immediate environment. Still others, and probably the largest bulk of recent work in science studies, are constructivists (Golinski 1998), and they explain specific instances from specific sources, i.e., the range of explanatory principles does not extend beyond the immediate environment of the local phenomena under study. What are we to do with this mess?

Salviati: Again, the point is not the details of their theories, but the general attitude. Causes are neutral, as opposed to reasons which always include some normative or evaluative element. Just as physicists don't evaluate natural processes but simply describe them, sociologists do not evaluate scientific beliefs. Descriptive neutrality requires that "true," "rational," "objective," "better," and other strongly normative concepts be withdrawn from scientific discourse (or, rather, better be made topics as connected to norms rather than resources). This lack of evaluative tone is often seen as evaluation itself, when it replaces a discourse which is usually evaluative.

Sagredo: A fine point. To cite a fitting analogy from Harry Collins (2001b, p. 157): sociologists want to explain why members of a certain community believe that wine can turn into blood, while members of another community don't. Because the "Yes" community maintains a positive evaluation of the norms that justify their belief, the analysis will be seen as downgrading their claim and its entire cognitive background together with it. At the same time, the "No" group will have the same impression regarding their own position, and for the very same reason, but the sociologist simply did not want to decide and hence take into account whether or not the wine can "indeed" turn into blood. Seeking a causal explanation as to why participants in the

Nazi regime behaved in the way they did, the account will be seen as making unwarranted excuses – this time because of the lack of the generally accepted negative evaluation attached to the matter. Now, we are accustomed to a discourse about science that is highly praising, and the lack of this positive tone seems degrading to many.

Simplicio: But this "neutral" discourse is useless when the educator's purpose is to build respect for science!

Sagredo: But it is only one of the purposes. Understanding how science works is another, and the heroic stories about Great Achievements of Great Minds do not do justice here.

Salviati: Let me offer another aspect here. Historian of science Steven Shapin (2001) added his voice to the Science Wars when, paraphrasing Sokal's famous hoax (Sokal 1996), he collected a list of statements expressing the credo associated with relativists and then revealed that all the statements were made by prominent scientists. One moral of the story is that while scientists agree in most scientific questions (i.e., their consensual knowledge base, excluding the very recent problems they dispute), they strongly disagree when it comes to metascientific commitments, since some share many relativist views (about the political nature of science, or the social contingency of our scientific concepts), while others stick to a picture of science as the inevitable voice of nature.

Sagredo: Statements, including these, "There is no such thing as the Scientific Method," "Scientists do not find order in nature, they put it there," "New knowledge is not science until it is made social," and others, are generally associated with constructivist and sociological approaches (Shapin 2001, pp. 99–100). A fine illustration of the point you cited from Lakatos early in our discussion.

Salviati: The claims that Simplicio would find degrading are made in specific contexts when "secrets of the trade" are revealed to attentive audiences, and this is the more relevant conclusion. In formal public settings where the esteem of science is at stake, the very same scientists pronounce more "polite" statements in better accordance with the usual expectations. Quite contrary to metascientific statements in mathematics (Davis and Hersh 1981, p. 321), many scientists are constructivist on weekdays and inevitabilist (Hacking 1999, p. 79) on Sundays. Just like in a family, problems are explicit only for friends, but everything is fine for the wider public. Trevor Pinch (1986), when interviewing researchers of the solar neutrino project, found that those who admitted possible weaknesses in their work did it in a form resembling secret initiation rituals. But if we rely on scientists' white lies in science classes, students are misled – and, as Sagredo pointed out, they get disappointed later when they face reality.

Simplicio: Alright, I concur that this enthusiastic but small circle of SSK offers their descriptions with fair intentions. But what about those numerous "xxx-ist" and "post-xxx-ist" people from the humanities I mentioned earlier, whose explicit goal is to criticize, desacralize, and "unmask" science? Am I supposed to tell our students that modern science is capitalist, masculinist, and politically oppressive and that it is an obsolete “grand narrative” that we should best dispense with?

Sagredo: It is virtually impossible to pretend that science is for the pure benefit of humankind, in an independent and culture-transcendent niche. Science has always been embedded in a cultural environment interwoven with technological, economical, social, political, and all kinds of aspects, and it is hard to deny that science has grown huge and powerful, fundamentally shaping modern technological and information societies. A large proportion of recent sociological case studies therefore focus on science policy, politics of science, innovations, risks, stakeholders, and all kinds of stuff that are clearly relevant to students, regardless whether they would become scientists or not.

Simplicio: I understand how these matters are relevant to would-be scientists, but I am not sure why they could be of great interest to laypeople.

Sagredo: Consider “the third wave” in science studies, advocated by Harry Collins and Robert Evans (2002) in a paper that has become one of the most cited works in the field. By blurring the boundary between experts and the public and replacing it with a “periodic table of expertises” (Collins and Evans 2007, p. 14) in a program called “Studies of Expertise and Experience” (SEE), the paper attempts to conceptualize decision making in mixed policy settings. The first wave tried to account for the success of science as taken for granted – and traditional sociology of science would represent this tenet. The second challenged the automatic respect and offered naturalized descriptions of science as a profoundly human endeavor – that would be SSK and its many subsequent versions.

Salviati: I like toying with the idea of different kinds and degrees of expertise, especially “meta-expertise” (Collins and Evans 2007, pp. 45–76) that refers to the skills by which we, laypeople, become able to assess expert claims….

Simplicio: You must be joking. If an expert, by definition, is far more knowledgeable than a layperson, how can the latter legitimately evaluate what the former states?

Salviati: By relying on social discrimination rather than technical knowledge. If two experts disagree, I can check their credentials, positions, ranks, track records, etc. Most people have no sufficient grasp, for instance, of the theory of evolution to judge whether Intelligent Design protagonists are probably right or probably wrong, but they can still assess the approximate proportion of experts supporting the confronting views, or the statuses of their publication forums within the scientific community, or their ranks and credentials, or the relevance of their research background, or the origin of funds supporting their institutes, and so on. And I claim that one can reach a pretty secure judgment here, without having to become an expert oneself. However, and this is what makes me uneasy here, SEE explicitly rejects the purely descriptive stance taken by what they call Wave 2 and advocates normative intentions to guide us in our meta-expert decisions.

Sagredo: And why does this bother you? Why not be normative in classrooms? Descriptive neutrality becomes impotent when your students ask you whether they should believe the theory of evolution or supporters of Intelligent Design, or when they ask your opinion about table dancing, or when they seek your advice in going to see what kind of doctor or spiritual healer or shaman…Would you leave them with a Feyerabendian riddle about "anything goes" for the lack of no rational decision standards?

Salviati: I may be an expert at science education, but I am no scientific expert in all questions. I want to prepare my students to be able to decide for themselves, rather than follow my authoritative voice.

Simplicio: And then they need to acquire criteria according to which they make their decisions, and I do not see how you can avoid being normative here. You can't introduce your students to every single approach that ever existed and say, I don't know which one is the best, see for yourselves! … I actually like the idea of social discrimination. If meta-expert assessments depend on judgments about ranks, publication forums, institutes, and such kind of things, then it is the first wave, sociology of institutions, that we need to teach – but only the essential basics, of course. The relativist second wave is useless here.

Sagredo: Far from that. The emphasis for most relativist authors is not on the theories we discussed, but on the detailed case studies they offer to reveal how science works. If you want to understand the social dimension of science, you need to see the contingencies inherent in laboratory research, communication and interpretation of results, choices of method and theory, settling controversies, etc. – and this is precisely what the so-called Wave 2 has taught us. The image of science offered by popular movies and books or, for that matter, the image offered by popularizing literature can hardly be matched with the actual practice of science. If SEE calls for the use of social intelligence and argues that modern people acquire a fair bit of this intelligence just by being immersed in society, then my answer is that this general discrimination becomes insufficient when facing science. Laypeople hardly know any details of how scientists work, so how could we expect them to be meta-experts in a world of scientific expertise?

Simplicio: Why not let them rely on expert testimony? Let them believe what expert say, for this is why we have experts: they bear the epistemic authority and responsibility.

Salviati: Your suggestion turns on the validity of the so-called deficit model for the public understanding of science. It sees laypeople as passive in receiving scientific knowledge, and it relies on a premise that is modeled on the traditional science classroom situation, namely, that laypeople (like students) are viewed as yet ignorant of science but capable of having their head "filled" with knowledge diffusing from centers of knowledge production.

Simplicio: Such a process is beneficial since it increases laypeople's scientific literacy (and their ability to solve related technical problems), and their degree of rationality (following the rules of scientific method), and finally, their trust in and respect for science. Can you offer something better?

Sagredo: Surely, if you consider the way laypeople and scientists meet in our present cultures. According to the far more plausible premise of the so-called contextual model (Gregory and Miller 2001), members of the public do not need scientific knowledge for solving their problems, nor do they have “empty memory slots” to receive scientific knowledge at all. Instead, the public’s mind is filled with intellectual strategies to cope with problems they encounter during their lives, and some of these problems are related to science. So the active public turns to science, more precisely to scientific experts, with questions framed in the context of their everyday lives. After all, we live in a world where most tasks are best performed, and most questions best answered, by specific people with outstanding skill and knowledge base, called experts.

Simplicio: And what is the difference between saying that scientists teach us how the world is and saying that our questions are answered by scientific experts? Isn’t it a fancy way to express old trivialities?

Salviati: Not at all. The questions the public is interested in can rarely be answered by “ready-made science” deposited in textbooks; they belong to “science in the making” (Latour 1987). Instead of asking how planets or pendulums precisely move, to which there exist answers that are consensual and yet mostly irrelevant to the public, they want to know, e.g., what materials or activities are healthy. These questions are (still) controversial in science, and nonexperts are faced with a plethora of different and partly contradicting expert opinions, from which they have to build their own system of beliefs.

Simplicio: I may object that scientific experts would always reach a consensus if they were given enough time, but you would probably object that decision making in politics and economics is usually faster than consensus making in science, if we take the post-academic scenario for granted…

Salviati: Or the post-normal scenario (Funtowicz and Ravetz 1993), according to which decisions in the science and technology of our age are achieved under the circumstances of high risk and uncertainty.

Sagredo: So many concepts, so many challenges and aspects and approaches… One thing we found is that the social studies of science has clearly developed, become a field of expertise that has increasing relevance for science educators. As our image of science and the institutions of science change, this is reflected in our educational system, in the mindset of students, teachers, policy makers, and other stakeholders. The lessons of this discipline – even when at times it appears that it is not too disciplined – can help inform both the teaching practice and the theory of science education. But I am afraid we need to conclude our discussion, as we all have our classes to teach. I hope that we will find our discussion inspiring.

Simplicio: No doubt. A major lesson for me is that sociologists have efficient tools to study the practices of science. To see their results is important not only to students planning to pursue a scientific profession but to the wider public also, for science is an essential vehicle of modern social progress.

Salviati: To which I may add the following: student understanding of science can fruitfully extend beyond popular and ideological representations, by utilizing the knowledge of the discipline that pursues the practice of scientists in a historical, cultural, technological, and economic context.

Sagredo: And all this implies that one-sentence retorts about science, sold as "nature of science," watery metaphors, fancy analogies, or simplified algorithms of methodology can hardly capture the knowledge needed to develop understanding of what science is. The knowledge that scientists know about nature and about science are both essential ingredients of science education.

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Chapter 35
Generative Modelling in Physics and in Physics Education: From Aspects of Research Practices to Suggestions for Education

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35.1 Introduction

The past decade in science education research has seen extensive discussion of the model-based view (MBV) of science education. Much of the inspiration of the model-based view derives from the notion that models are central knowledge structures in science and vehicles for developing, representing and communicating ideas. Hopefully, focusing attention on models as core components of knowledge will make it possible to produce a more 'authentic' picture of science than that currently offered in school science. Consequently, educational researchers expect the model-based approach to deeply affect future curricula,[1] instructional methods and teaching and learning in general, as well as teachers' conceptions of the nature of science.[2] The views put forward in favour of the model-based view have generated discussion of the epistemological goals of science education as well as produced new approaches to science education. However, question remains: In what areas has the MBV brought us closer to an authentic picture of science and in what areas is there still work to be done?

Many researchers advocating the MBV have sought support from the philosophy of science for the focused and coherent use of a philosophical framework for purposes of research in learning,[3] for practical teaching[4] and for designing didactical approaches in general (Izquierdo-Aymerich and Adúriz-Bravo 2003). However, not only are views of the philosophy of science of interest but also the philosophical

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[1] See, e.g. Gobert and Buckley (2000), Justi and Gilbert (2000), and Izquierdo-Aymerich and Adúriz-Bravo (2003).

[2] See, e.g. Justi and Gilbert (2002), Oh and Oh (2011), and Van Driel and Verloop (2002).

[3] See, e.g. Adúriz-Bravo and Izquierdo-Aymerich (2005), Develaki (2007), and Nola (2004).

[4] See, e.g. Crawford and Cullin (2004), Halloun (2007), Hestenes (1987, 1992), and Sensevy et al. (2008).

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underpinnings of the recent science studies on scientific practices still need attention and reconsideration. Such reconsiderations are needed to define the essential epistemic aspects of models and modelling in building scientific knowledge and how education could highlight such views on modelling practices. For example, what the MBV has not yet taken into account is that the value of models in scientific practice largely depends on how they can serve as somewhat autonomous, freely developing tools of creative thinking and for exploring theoretical ideas. Indeed, from the viewpoint of the goals of science education to promote higher learning and creative thinking, models as tools of thinking deserve attention. Consequently, this article focuses on the role of models as tools of thinking and as vehicles for creative thought, which we refer to here as 'generative modelling'. Such generative modelling shares many aspects with the 'constructive modelling' and 'generic modelling' discussed by Nersessian (1995, 2008). Following Nersessian, we also draw support from recent science studies of ways of thinking and of practising scientists' use of models. The viewpoints of practising scientists are often flexible and dynamic (as we will discuss later in this article), allowing the employment and development of different kinds of models in the different states of knowledge-building practices. In generative and constructive modelling, the 'running of a model' – either mentally in the form of simulative reasoning or more methodically by using computing algorithms and computers – unfolds the system's dynamical behaviour. The dynamic unfolding of the model in simulations is important because it plays a role both in developing the model and in understanding the processes behind various phenomena through modelling. However, although the purpose of such modelling is to understand phenomena, the models may not be always realistic representations of the systems of the processes. Nevertheless, such models can often play an important role in creative knowledge building because they act as tools for exploring theoretical ideas.

In Sect. 35.2 of this article, we first briefly describe contemporary views of models and modelling in the philosophy of science while emphasising the autonomy of models and their use as tools of thinking and reasoning and in exploring conceptual ideas. A brief summary of current model-based views in science education appears in Sect. 35.3. Because both areas are too broad for a thorough review here, we discuss them insofar as to show that the practices of modellers support the idea that in modelling, (1) models serve in semi-autonomous ways, (2) models mediate between experiments and theory and (3) models are instrumentally reliable rather than 'true'. Sect. 35.4 develops these theses in more detail on the basis of the background outlined in Sects. 35.2 and 35.3. Ultimately, Sect. 35.5 embodies the claims in Sect. 35.4 by providing empirical data from interviews with modellers in the field of materials physics and nanophysics. Lastly, Sect. 35.6 discusses the implications for science education.

35.2 Views of Models and Reality

The philosophical underpinnings of models and modelling directly touch upon philosophical issues concerning the relationship of theory to the world as experienced or how we access reality through experiments and how we express this understanding in abstract theoretical form. In this process, models play a central role. Current science education discusses these relationships and the role of models in it under various names, such as the 'new view on theories' (Grandy 2003), 'new history and philosophy of science' (Izquierdo-Aymerich and Adúriz-Bravo 2003) and 'cognitive theory of science' (Giere 1988). All these views are more or less related to the semantic view of theories (SVT) that originates from the work of Suppes (1962), Suppe (1977), van Fraassen (1980) and Giere (1988). In the SVT, the task of theory is to present a description of phenomena within its 'intended scope' so that one can answer questions about the phenomena and their underlying mechanisms (Suppe 1977). In the SVT, the phenomena (as isolated physical systems) are addressed in terms of models, and theory is identified with a set of models (van Fraassen 1980, Giere 1988, 1999). The best-known positions within the SVT are probably the constructive realism of Giere (1988) and the constructive empiricism of van Fraassen (1980), which offer somewhat different answers to the question of how models represent and what their relationship is to theory.

Within the SVT, researchers in science education have recognised the realistic position of Giere (1988, 1999) as a viewpoint which may more closely link science and science education.[5] One reason for this is that Giere's philosophy of science focuses attention on the cognitive and pragmatic factors involved in *doing science*. Another reason is that Giere outlines the relationship between models and reality through realism as embodied in the *notion of similarity*. The model presumably represents, in some way, the behaviour and structure of a real system; the structural and process aspects of the model are similar to what it models. According to Giere, one can describe the theory in general as a cluster of models or 'as a population of models consisting of related families of models' (Giere 1988, p. 82). In Giere's model-based view, the question of theory is therefore not central, because there is already 'enough conceptual machinery to say anything about theories that needs saying' (Giere 1988, p. 83). It seems that such a semantic view, with its accompanying realism, is the favoured position of current views within science education that seek an authentic image of science.[6]

Currently, the SVT and versions of it within philosophical realism provide a robust background to use models and modelling for purposes of science education in the context of predicting and in explaining. However, the current positions must be reconsidered in order for it to correspond to scientific knowledge building. For example, the most favoured contemporary views say little about the methodological aspects of producing a relationship between models and the world, as one accesses it through experiments. However, this question is of central importance for both building scientific knowledge and learning science and thus deserves further consideration. A suitable departure point for this is to examine scientific practices in modelling.

The SVT and versions of it within philosophical realism are thus promising candidates for a robust background philosophy for science education, but they require further development. At least in physics and physics education, Giere's conception

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[5] See, e.g. Adúriz-Bravo and Izquierdo-Aymerich (2005), Crawford and Cullin (2004), and Izquierdo-Aymerich and Adúriz-Bravo (2003).

[6] See, e.g. Gilbert et al. (2000), Matthews (1994/2014, 1997), and Nola (1997).

of models (as well as the SVT itself) requires some revision for the following reasons. The SVT does not consider the bidirectional relationship between the model and the experimentally accessible phenomenon. It is helpful to compare the bi-directionality with Giere's views of how models are matched with experiments (Giere et al. 2006). In that picture, the similarity or fit of models with real systems is evaluated on the basis of agreement between experimental data and model predictions, but these schemes entail no feedback between the construction of models and the design of experiments or the process of isolating phenomena by altering the experimental setup (Giere et al. 2006, pp. 29–33). To properly and explicitly take into account the bi-directionality, one must realise that when models serve to explain phenomena, the phenomena are not only modelled but are also fitted to the models (Cartwright 1999). Indeed, the concept of similarity (Giere 1988) must be clarified in order to understand the process of matching a model to real systems – and what such matching really achieves. Taking similarity in as strictly realistic a way as possible (as a similarity of representation) is questionable in physics education, because physics offers no compelling reason to include this requirement among the attributes of good models. In what follows, we discuss in greater detail what such empirical reliability means and how it is achieved, as well as the extent to which these are pragmatic, methodological and epistemological questions that can be approached by examining scientific practice.

A second revision – or rather extension – of the standard SVT involves the semi-autonomy of models (from both theory and experimentation) noted in science studies focusing on the usage and development of models as tools in scientific practice (Morrison and Morgan 1999; Morrison 1999). The autonomy of models is closely related to the question of the relationship between models and theory. In the description provided by Morrison and Morgan (1999), models are largely independent of theory. As Morrison argues, the autonomy of models hinges on two notions:

> (1) the fact that models function in a way that is partially independent of theory and (2) in many cases they are constructed with a minimal reliance on high level theory. (Morrison 1999, p. 43)

However, this does not mean that theory plays a negligible or small role in model building and design. Morrison also emphasised this point noting that models 'are not strictly "theoretical" in the sense of being derived from a coherent theory, some make use of a variety of theoretical and empirical assumptions', which means that models 'obviously incorporate a significant amount of theoretical structure' (Morrison 1999, p. 45). Physics offers several examples of this kind of model-theory relationship. For example, models within complex systems – in particular the archetypical cases of the Ising model and spin-glass models – cannot be 'derived' from any theory, nor it is necessary to define exact 'similarity' between the spin elements of the model and their counterparts in the reality they are intended to model. Instead, the elements and the interactions of the model are meant to stand in some relevant structural relationship to each other, corresponding to the real system, so that the model can reproduce the generic features of the real system (e.g. collective behaviour in some physical disordered or magnetised system but equally well in a sociological or ecological system). Although such a model is not derived from theory, the construction of such models entails many theoretically guided steps.

The theory-to-model relationship has been discussed also by Winsberg (2001, 2003, 2006), who remarks that even though models are not derived from theory, theory nevertheless guides model development. The examples Winsberg provides are typically instances in which a rather well-established theory, such as hydrodynamics or continuum mechanics, already exists, and which allows derivation of a set of dynamic equations in the form of differential or difference equations, but which are not necessarily solvable without further modelling. Consequently, Winsberg argues that such models and modelling are rather semi-autonomous than autonomous. In addition, Winsberg seems to hold position that modelling aims to represent real systems, which, on the other hand, he takes as the most essential epistemological dimension of the use of models and modelling. There is no doubt that Winsberg's position is good departure point in cases that involve established theory as a starting point for modelling a known target, such as hydrodynamic flows, nuclear explosions or the behaviour of plasma, where one can derive a governing dynamic equation for the collective behaviour of a system or its parts. Upon closer inspection, however, Winsberg's examples differ substantially from cases encountered, for example, in complex system behaviour, or even more traditional field of nanosystems, where neither an established theory nor well-known targets exist in the sense discussed by Winsberg. In such fields of research, modelling is more a tool for thinking than a tool for realistic describing and predicting. Consequently, the purpose of modelling is to provide a means for simulative reasoning (cf. Nersessian 1995, 2008) and extended means for performing thought experiments. To perform in the desired manner, such models and modelling must be sufficiently autonomous. However, as Winsberg (2001, 2003, 2006) noted, this does not mean complete independence from theory; theory plays the role of providing guidance, but at the same time, much freedom to use non-theory-derived elements is necessary.

In what follows, we focus on the example of nanophysics, which provides an interesting border case; we have every reason to expect a clear theory-to-model relationship (the research field is, after all, rather conventional branch of materials science), a preference to strive for realistic descriptions and attempts to establish similarity. Somewhat contrary to these expectations, however, simulation practices in nanophysics reveal several extra-theoretical elements, clear instrumental rather than realistic positions are recognised, and instead of similarity with real systems, practical values for reasoning and a certain type of mimetic similarity (though not in the sense of direct visual similarity) emerge as a part of it. Since these findings are from the field of materials science, similar attitudes and stances may also be typical of many other branches of the physical sciences. After all, using models as tools of thinking rather than as tools for realistic representations, or striving for instrumental and practical values instead of realism, may in practice prove far more common than that envisioned by philosophers holding to realism and especially to representational realism.

Nersessian (1995, 2008), who viewed models as means (and tools) to represent ideas as well as reality, emphasised the cognitive aspect of using models with no overarching emphasis on philosophical realism. For this, the SVT is a suitable framework, as it suits views inclined towards philosophical empiricism, realism and pragmatism equally well. The SVT can be seen as a structure or net of models related to each other in different ways and in which mutual relationships are under development. Viewing the SVT in this way leaves room for the generative, mediating models. Such an interpretation of the SVT permits greater independence of models from theory as well as a loose relationship within the set of models, yet without requiring a hierarchical relationship of models, as Giere describes (1988, 1999). Such interpretation provides sufficient, if not complete, freedom from theory and empiry to warrant the phrase 'autonomous models'. In what follows, we show that the modelling practices encountered in physics quite well support the argument that models are semi-autonomous but that at the same time, their design is theoretically guided (without being derived or deduced from theory). Such semi-autonomous models are sufficiently free from theory to be useful for developing of theory and making them interesting enough as objects of research in their own right.

From this background, we propose here a revision which, for the most part, still fits within the SVT but relaxes some of its restrictions. The decision to concentrate on physics stems from the notion that in physics, the role of models and modelling is epistemologically and methodologically essential. Consequently, the process whereby theoretical predictions are linked to the outcome of measurements plays an important role (Koponen 2007). One goal of the present study is to encourage science education to reflect as much as possible the epistemological aspects of doing science as well as aspects with which practising scientist can also agree. This goal can be called providing an 'authentic picture of science'. The current study attempts to provide just such an authentic picture of models and modelling in physics. From this viewpoint, there is no compelling reason to limit views only to those within philosophical realism, which seems to be the preferred way for the current science education literature to view models and modelling.

This article discusses models and modelling from the viewpoint of physics, which then serves as a philosophical background for developing physics education. We first scrutinise recent views of models and modelling in science education in order to outline their philosophical underpinnings and to support the argument that this philosophical basis requires revision. Next, we discuss the question of making a match between theory and experiment, and the role of models and modelling therein, from the viewpoint of recent science studies. We then explore these ideas in the light of an empirical study of modelling scientists' views of their knowledge-building practices. Against this background, we argue that an authentic image of models and modelling in physics requires a certain bi-directionality; models, which respect central, established theoretical ideas, are developed to match phenomena as they take place in laboratory experiments. Indeed, what matching produces is both a functional model, a particular experimental system which can then be modelled, and new knowledge about the phenomenon under consideration. Finally, we suggest that, at least in physics education, the requirements of empirical reliability and empirical success in advancing experimentation are attributes that better correspond to an authentic image of scientific modelling than those of realism and truth, as understood in the philosophy of science.

35.3 Models and Modelling in Science Education

The role of models in providing explanations and predictions is perhaps the most common area in which epistemological questions are explicitly discussed, and in this role, models and modelling are often seen from the point of view of realism.[7] The moderate realistic viewpoint is clearly reasonable from the viewpoint of learning. However, the preferred role of realism in supporting a model-based view is often based on the notion that realism is also the preferred view of the scientists who employ models and modelling and that therefore this kind of approach ensures an 'authentic picture of scientific modelling' (see, e.g. Schwarz et al. 2009; Pluta et al. 2011). Such claims are mostly not justified by argumentation based on the philosophy of science nor are there evidence based on analyses of science practice.[8] Of course, claims of authenticity then rest on weak standing. Before we suggest how to expand viewpoints on models and modelling, we briefly discuss how the relationships between theory, model and experiments are conceived in certain practical solutions for school science.

One of the first suggestions for how to use models and modelling in physics education is Hestenes's (1987, 1992) approach, which underscores the relationship of models to theory and experiment. According to Hestenes, model construction follows comprehensible rules (the rules of the game); models are then validated by matching them with experiments. Hestenes draws insights from Bunge's conception of models and parallels Bunge (1983) when he emphasises the mathematical structure of models and their subordination to theory. Hestenes's ideas reflect a clear predominance of the verificative justification of knowledge, and the truth value of models is judged according to the success of such theory-based predictions. This reflects scientific realism, which adopts not only ontological but also epistemological and methodological realism. When known and accepted theory serves as a basis for making predictions, the aspects Hestenes stresses in modelling clearly constitute an authentic way of modelling in physics. Such theory-based modelling of physical situations also occurs in empirical research in mathematics education that aims to combine mathematical and physical modelling, most often in the field of classical physics (e.g. Hestenes 2010; Neves 2010). This view is justified in the context of making predictions and providing explanations, which are surely the most important aspects of school science, which typically employs models and modelling and presents them as a means to illustrate scientific content (Hestenes 2010). In addition, relying on Hestenes's modelling rules makes it relatively clear how to develop teaching solutions and design teaching activities. Following the modelling methods recommended by Hestenes, traditional physics teaching where theory comes first evidently leads to improvement (Wells et al. 1995; Halloun 2007). However, such an approach loses its teeth in the context of scientific knowledge building,

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[7] See, e.g. Gilbert et al. (2000), Hestenes (1992), Justi and Gilbert (2000, 2002), and Nola (2004).

[8] Analyses of science practice in fact provide evidence pointing to the opposite conclusions (see, e.g. Koponen (2007) and Tala (2011) and references therein).

where the main interest is in the construction of theory or the acquisition of knowledge not already captured by existing theory.

A related approach from theory to models, but somewhat less theory subordinated, is found in the work of Crawford and Cullin (2004), where the main epistemological role of models is in explaining and developing understanding of the phenomena of nature. According to them, the scientific process can be depicted as a sequence of making observations, identifying patterns in data and then developing and testing explanations of these patterns; in their words 'such explanations are called scientific models' (Crawford and Cullin 2004). In the modelling activity described by Crawford and Cullin, students observe, indentify variables and conceive ideas about the relationship based on their own ideas, which they then test. These authors do not explain their epistemological position with regard to models, but the realistic stance and role of models in providing explanations is apparent on the basis how they refer to the philosophical works of Giere (1988, 1999), Hesse (1963), and Black (1962) in what they discuss about model-to-reality correspondence or similarity. In all cases, a question is the realistic one: How do models represent real systems and how can one improve this correspondence? An adherence to realism is also evident in their general purpose of 'investigating real-world phenomena; then designing, building, and testing computer models related to the real-world investigation' (Crawford and Cullin 2004, p. 1386). They do not explain how these models are produced or how they relate to theory, but taking into account the philosophical underpinnings to which they refer, something close to Giere's concept of similarity between the models and the real world seems to be involved.

The picture of models and modelling proposed by Halloun (2007) is closely related to Hestenes's views in that it sees the role and use of models in making predictions and explanations in a realistic sense. In addition, Halloun focuses to the role of models in investigating and controlling physical systems and phenomena, as well as in influencing the development of a scientific theory. These aspects are important for modelling, which is not theory constrained, but is instead theory generative (cf. Koponen 2007). In agreement with this, Halloun notes that

> For meaningful learning of science, students need to systematically engage in identifying and modeling physical patterns and explicitly structure any scientific theory around a well-chosen set of models. (Halloun 2007, p. 655)

To achieve this, he proposes a modelling scheme, which begins with (1) physical realities and then (2) identifies a pattern for which (3) a model is constructed. This continues with (4) analysing a model and (5) inferring pertinent laws on which one makes predictions (and perhaps also inferences) of the physical realities. Finally, on this basis, (6) the model is refined and integrated into the existing theory (theory may then change) (Halloun 2007, p. 663). In fact, these three steps can be seen as basic steps in creative modelling, which are capable of generating new knowledge, with the ultimate goal not only of predicting or explaining but also of intervening. The success in manipulating and intervening in the phenomenon then provides a basis for developing our understanding of the phenomenon in question. These aspects of modelling are seldom discussed in the context of the model-based view of science education, although such aspects are arguably the most central in advanced levels of scientific modelling (cf. Koponen 2007; Tala 2011).

One can hardly discuss models and modelling in physics without acknowledging the role of mathematics and mathematical thinking in knowledge in physics. To present modelling of a real system, the recent literature on mathematics education, often uses steps quite similar to those Halloun has suggested for modelling in physics. The steps constitute the modelling cycle of the iterative mathematical modelling process for a phenomenon as perceived in the real world. Mathematical modelling cycles are presented as including the identification and simplification of the problem or purification of the variables (cf. Halloun's step 1), formulation of the mathematical model of the real situation (cf. Halloun's steps 2 and 3), solving or studying the mathematical model (cf. Halloun's step 4) and then interpreting the mathematical results in the real world, which is then followed by an evaluation and the development of the model in a repeated modelling cycle.[9] Such mathematical modelling highlights the role of mathematising the phenomena and role of creativity involved in mathematical reasoning and thinking. Empirical research on such mathematical modelling education has proved to be an effective means for preparing students to deal with unfamiliar situations by thinking flexibly and creatively when solving concrete real-world problems by using applied mathematics (Haines and Crouch 2010; Uhden et al. 2012). Theoretical understanding requires focusing on the mathematical framework of modelling, which guides the analysis and simplification of the physical situation and interpretation of the results. Therefore, the viewpoint provided by mathematical modelling education can focus attention on the important role of mathematics in the physical modelling process and the development of mathematical or computational models in a modelling process.

Finally, discussing the creative process of modelling requires that one consider cognitive viewpoints. Nersessian (2008) has studied how scientists use models in discovery processes and to create theories and notes that in 'scientific discovery, models and modeling come first, with further analysis leading to formal expression in the laws and axioms and theories' (Nersessian 2008, p. 205). Scientists use models as cognitive tools, especially when creating, thinking and reasoning their way to novel conceptual representations by means of models.

For practising scientists, an important role of models functions as tools for intervention in and the manipulation of phenomena. Cartwright (1983, 1999) and Hacking (1983) and more recently many other authors (see Morrison and Morgan 1999) discuss this practical role of models. In addition some studies in science education (Izquierdo-Aymerich and Adúriz-Bravo 2003; Crawford and Cullin 2004) now also recognise this practical role of models as tools of thinking. For example, Izquierdo-Aymerich and Adúriz-Bravo (2003) discuss the role of scientific activity and scientific research as an attempt to transform nature and interact with it, rather than as an activity for arriving at truths about the world. They note that models (and theory) which fail to achieve these goals have little value in science education for students and teachers. Unsurprisingly, they follow Hacking (1983) in emphasising

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[9] See, e.g. Blum and Ferri (2009), Haines and Crouch (2010), and Uhden et al. (2012).

that models serve to make sense of the world, with the ultimate objective of actively transforming the ways to see nature, where ‘facts of the world are heavily reconstructed in the framework of theoretical models’ (Izquierdo-Aymerich and Adúriz-Bravo 2003). These new aspects concerning the use of models and modelling agree with the physicist’s conception of acquiring and justifying knowledge.[10] However, understanding these aspects of transforming, manipulating and intervening in phenomena requires that models serve as autonomous or semi-autonomous agents, much like research instruments.

The viewpoint which sees models as research tools for constructing, understanding and generating knowledge is interesting for education, because it assigns models an active role in the generative and creative process of knowledge construction. Sensevy et al. (2008) have discussed such use of models and modelling in school science from a viewpoint of how the modelling process enables transitions between the abstract and the concrete. In that, they make use of the views put forward by Cartwright (1983, 1999), and Hacking (1983) in a manner similar to that proposed by Koponen (2007), who also endorses Cartwright’s and Hacking’s views among those put forward by van Fraassen (1980). Sensevy et al. called this emerging view of models and modelling the New Empiricism, which emphasises the integral role of empirical knowledge in model building. This New Empiricism captures quite well the bidirectional roles of empirical and theoretical knowledge, not only in model building and interpretation but also how theory guides the empirical explorations as well as framing of phenomena (cf. Koponen 2007). For this type of picture, a weak realistic position, which emphasises the pragmatic aspects of knowledge, fits very well. Indeed, in this way, education allows room for students to construct their knowledge in an equally flexible way as do the more radical constructivist positions.

The generative and creative use of models is challenging for practical solutions of education, because such use of models requires the means to explore the behaviour of the model and to unfold the dynamic evolution of the model system. The behaviour of the model is then compared to the behaviour of the real system in order to understand which aspects of the system model capture and how the model describes. This requires simulations. Insofar as simulations make the dynamic evolution of the model system explicit, science education literature seldom addresses them. Usually, computer ‘simulations’ in science education are either ready-made programs, controllable animations of theoretical situations or programs being based on object-oriented programming rather than real simulations[11] (Crawford and Cullin 2004). What is missing from these applications is the possibility to transform the original mental constructions first to more formal model structures (mathematical structures) and then these structures to a form which enables one to ‘run’ (i.e. simulate) the models. Nevertheless, when models serve as vehicles generating new ideas and as tools in the creative exploration of ideas, simulations are indispensable.

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[10] See, e.g. Chang (2004), Heidelberger (1998), and Riordan (2003).

[11] See, e.g. Bozkurt and Ilik (2010), Finkelstein et al. (2005), Perkins et al. (2006), and White (1993).

Simulations in this sense, however, must not be conceived as ready-made computer programs or applets, which are rather simple animations with control parameters, but as computational or algorithmic tools which unfold or generate the dynamics the model relations contain, yet remain largely unseen in the model itself.

35.4 Generative Modelling and Simulations

Models in the role of constructing new knowledge, generating theory and as tools for discovery have seen relatively less discussion than have model-to-theory relationships, semantic conceptions of models or model-to-experiment relationships. According to Nersessian (1995, 2008), the role of models in constructing knowledge is most important for creative scientists but seldom addresses in teaching science. Of course, creative development and the construction of models are more difficult to discuss than, for example, theory-subordinated modelling, but on the other hand, having access to such modelling in teaching and learning science adds an important creative dimension to science education.

In her account of constructive modelling, Nersessian (1995, 2008) draws on historical analysis and its cognitive interpretation. According to Nersessian, constructive modelling is a kind of reasoning process that aims to integrate different types of knowledge structures, such as analogies, visual modelling and thought experiments, in order to provide cognitive means to explore and to reason about phenomena or target problems for which no direct model is available. The way Nersessian describes the content and purpose of such constructive modelling also applies into cases not only where direct analogies are missing but also where the ways in which to apply the theory remain obscure or attempts to do so fail (unlike in situations described by Winsberg, where seeing how the theory supports and guides model development is relatively straightforward). An important part of constructive modelling is so-called generic modelling, where ‘the generic model represents what is common among the members of specific classes of physical systems’ (Nersessian 1995, p. 212), which allows one to transform known models as a basis for exploring new unknown situations. Thus, generic modelling guides scientists’ problem solving or helps them recognise similarities between physical systems for new regularities. Constructive modelling, on the other hand, involves

> constructing analogous cases until the constraints fit the target problem. The models thus constructed are proposed interpretations of the target problem. Further, the ability to construct and reason with generic models is a significant dimension of the constructive modeling process. (Nersessian 1995, p. 209)

However, according to Nersessian learning such constructive modelling is challenging in teaching and learning, because it requires sound background knowledge and deep engagement to modelling and possibly also to simulations, knowledge and skills which cannot be expected in introductory levels of learning. These requirements shed some doubt on success of teaching solutions based on very simple ways to use models, very straightforward modelling tasks or on use of ready-made simulations, where the learners' own role in construction of models is moderate.

In what follows, we propose a view of modelling sharing many characteristics with Nersessian's constructive modelling but, here, in more restricted scope as they appear in higher education and in advanced education. In this type of modelling, simulations play a central role but now in the form of algorithmic simulations and computer simulations. Models and modelling, when used as tools to generate understanding and especially in the role of creating new knowledge, often require running models with a computer, namely, simulations. The purpose of such simulations is very practical: to acquire new knowledge of already familiar systems and to probe the behaviour of the simulations (used as tool of investigation) in new situations. This process also develops and transforms the simulation model itself. In simulations, models and modelling play a central role: Simulations are the process of 'running the models' in the virtual world in order to reveal the dynamic behaviour of a system of models. Here, such a combination of modelling and simulations is called *generative modelling*. The practical character of generative modelling makes it a promising case for learning about the epistemological purposes of modelling, to be implemented also as a part of modelling in physics education.

The epistemological value of generative modelling in physics derives from its ability to bridge theoretical ideas – conceptual reality – and real systems. To understand this role, we must consider the relationship of generative modelling to experiments and theory in a balanced manner. Interestingly, this relationship is autonomous; although theory is deeply involved in constructing the models behind the simulations, the models only seldom derive from some underlying theory. This means that a model and the virtual environment provided by simulation respect the central theoretical ideas, but are not directly derived or deduced from theory. In simulations of nanostructure growth, for example, the principles of statistical physics, such as general conditions for equilibrium states and detailed balance, are respected, but the form of probabilities determining the dynamics of the system comprises often purely phenomenological models. Similarly, the relationship of models and simulations to experiments is intriguing; although simulation results are often compared to experimental results in order to verify or develop the simulation model or the simulation environment, this comparison often does more in that it may even affect experimental design and strongly influence which aspects of experiments will be considered. This suggests that the epistemological importance of generative modelling is related to its semi-autonomous role in theory and experiments and that it is this semi-autonomous position which enables generative modelling to 'mediate between the theory and experiment' (Morrison 1999). The way this mediating presents itself involves not only constructing the models to fit the phenomena but also finding and isolating phenomena to fit the models used in the simulations (cf. Cartwright 1999). Consequently, the models need not be faithful to all experimental results; there is freedom to ignore experimental aspects considered irrelevant without strict criteria for how to assess such relevance. On the other hand, the models remain free from theory in the sense that they need not be derived from theory (they must be in accordance with most important theoretical principles, although the criteria for ‘most important’ change from one situation to another). It is this semi-autonomy and flexibility of models which makes them so useful and practical in fitting together the conceptual (theoretical) and material (experimental) control of the phenomena under study and, through that control, providing new knowledge and advance theory construction.

Recent philosophical analyses of simulations and modelling provide several insights into how to frame the idea of generative modelling. First, generative modelling aims to be representative, but does not aim towards a realistic representation of physical systems and their behaviour. Instead, modelling involved in simulations purposely distorts some aspects of the systems to be represented in order to achieve its goal of more effectively representing the features of reality under scrutiny. Such a position can be described as selective realism (Humphreys 2004) or moderate realism (Koponen 2007). Second, generative modelling uses nested structures of different types of models (some of which are theoretically guided, and others, purely phenomenological) but in such a way that they constitute co-ordinated parts of the model. This resembles Hughes’s notion of the nested structure of successive modelling steps with nested representations in an ascending level of abstraction (Hughes 1997, 1999). Also, running simulations in order to unfold the process aspects of the phenomena is central to Hughes’s scheme. Third, unfolding the processual aspects of model systems in simulations is closely related to the notion of mimetic capabilities and mimetic similarity (Humphreys 2004). On this basis, notions which must be taken into account when discussing the purposes and capabilities of simulative modelling are as follows:

1. *Mimetic similarity*. Simulative modelling aims to establish partial mimetic similarity between the processual evolution of systems in simulations and corresponding (though not exactly similar) systems in experiments.
2. *Instrumentally reliable models*. Simulative modelling serves to construct and validate *instrumentally reliable models for the processes* behind experimentally accessible phenomena. These models embody the knowledge achieved by producing and developing simulation models.
3. *Generative modelling mediates* between high-level generic models (or theory) and experimentally accessible phenomena by constructing instrumentally reliable models and fitting them to phenomena. In that process, laboratory phenomena are also designed to fit the models better.
4. *Generative modelling is an instrument* of investigation relating to the world of concepts and theories (and experimentation) in parallel fashion to the way in which the measurement instruments relate to real systems; both are probes in their own worlds, about which they deliver information.

The first notion takes mimetic capabilities as central to knowledge production. Mimetic similarity between processes in simulations and those observed in experiments is at the core of the model justification process. It should be noted that mimetic similarity as understood here, however, is not simply visual mimetic similarity. As Winsberg (2003) has noted, mere visual similarity is of little epistemic value and deserves little attention. Similarity in generic behaviour or in the succession of unfolding events or processes between model systems and real systems, however, is of epistemic value, because such similarity between connected events carries information about causal knowledge or the determination of events. Hughes, for example, refers to such mimetic similarity, achieved through simulations, when he notes:

> The dynamic has an epistemic function: it enables us to draw conclusions about the behaviour of the model, and hence about the behaviour of its subject. (Hughes 1999, p. 130)

Epistemologically, however, this is possible only if models have *representative capabilities*. But 'to represent' now means something other than simply picturing, mirroring or mimicking physical systems, or being 'similar' to a real system. Instead, as Morrison and Morgan outline,

> a representation is seen as a kind of rendering – a partial representation that either abstracts from, or translates into another form, the real nature of the system or theory, or one that is capable of embodying only a portion of a system. (Morrison and Morgan 1999, p. 27)

In their words, such a 'model functions as a "representative" rather than a "representation" of a physical system' (Morrison and Morgan 1999, p. 33). In nanophysics, for example, such mimetic similarity is achieved when a spontaneous selection of order or sizes of nanostructures are generically similar in both real measurable systems and a simulated generic model of self-organisation. Successfully acquiring this similarity in simulations leads to greater insight and understanding, thereby producing knowledge. Similar type of mimetic similarity and its importance for knowledge generation without visual similarity is discussed also by Humphreys (2004) and Hughes (1997, 1999).

The second notion claims that instrumentally reliable models are the goal of modelling. It calls attention to the notion contained in selective or moderate realism that models must be empirically reliable descriptions of only certain aspects of processes and that only some of these selected aspects must be empirically validated. Such instrumentally reliable models are often the products of simulative modelling and also enable one to match theoretical ideas with experimental data, thus bridging the conceptual and the real. Instrumental reliability is important to the credibility of models and their epistemic credentials. On such instrumental reliability, Suárez (1999) notes that the degree of confidence rather than degree of confirmation is essential. The degree of confidence in the model, on the other hand, increases through its successful applications. This is a pragmatic virtue, achieved through use of models. In addition, methodological questions about how the production and design of models relate to pre-existing models and modelling methods are also important (Winsberg 2006). This is a kind of methodological continuity which increases the models' reliability. For scientists, such reliability, achieved through pragmatic and methodological credentials, is often sufficient, and questions of 'truth' in the philosophical sense do not play a major role (see, e.g. Riordan 2003). As Winsberg has noted: 'The success of these models can thus provide a model of success in general: reliability without truth' (Winsberg 2006, p. 16). Together these positions mean that in terms of the reliability of and confidence in models, the 'truth' of the models is less important than the realistic position assumes.

The third notion details the well-known claim that 'models mediate' and suggests how to clarify the vague notion of 'mediating'. Namely, modern experiments provide opportunities for precise control, thus allowing us to 'build our circumstances to fit our models' (Cartwright 1999) and thus narrow the gap between models and real systems. As Cartwright notes:

> …we tailor our systems as much as possible to fit our theories, which is what we do when we want to get the best predictions possible. (Cartwright 1999, p. 9)

She argues further that it is this very aspect of experimentation that makes theories (and models) successful:

> We build it [the system] to fit the models we know work. Indeed, that is how we manage to get so much into the domain of the laws we know. (Cartwright 1999, p. 28)

Accepting these views – evident in the practice of physics – means understanding models as matchmaking tools as well as for manipulating and isolating phenomena.

However, between the real world of entities and phenomena and theory (with its concepts), no direct connection or correspondence exists. Neither are the entities of the real world or its phenomena directly accessible through observation and experimentation. Only through laboratory experiments and measurable quantities do the regularities contained in phenomena or the entities behind them become accessible, observable (or detectable) and discernible. It is such an experimental law – a kind of 'model of data' – that the theoretical models constructed in physics are meant to be matched. The form of models we are interested in here mediates between high-level theory and experimental laws in the above sense. Several philosophers[12] have recently discussed the role of models as mediators between theory and experiment. These views reminded us that models are seldom constructed or derived from theory, nor do experimental data necessitate the models; rather, the models are built using knowledge from many independent sources, sometimes even contradicting the theory.[13] Nevertheless, models carry a substantial amount of well-articulated theoretical knowledge through the theoretical principles involved in their construction; otherwise, they would fail to perform their task of mediating between theory and experiment (Morrison and Morgan 1999; Morrison 1999). To focus on the semi-autonomous role of models, relaxing only the models' close dependence on theory contained within the SVT seems sufficient.

If experimental laws are also taken as models representing the data in suitable form, the emerging picture begins to resemble Suppes's (1962) view, where a hierarchy of models mediates between theory and measurements. This is a process of mutual matching, which entails sequentially adjusting and transforming both kinds of models and involves different levels of models. An essential feature of this bidirectional process is that models can fulfil their task of connecting experimental results to theory 'only because the model and the measurement had already been structured into a mutually compatible form' (Morrison and Morgan 1999, p. 22).

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[12] See, e.g. Cartwright (1999), Hughes (1997), Morrison (1999), and Morrison and Morgan (1999).

[13] See, e.g. Cartwright (1999), Morrison (1999), and Morrison and Morgan (1999).

Such a process of sequential matchmaking is inherently connected to the use of measuring instruments and the theoretical interpretation of their functioning, an aspect Duhem (1914/1954) already emphasised.

For Suppes, comparison between theory and experiment consists of a sequence of comparisons between logically different types of models. Darling (2002) has described Suppes's view by using the scheme of a 'data path' and 'theory path', which converge at a point where comparisons of data and theoretical predictions are possible. On the theory path, one begins by extracting from a physical theory principles or conditions relevant to the class of experiments under question. These data sets (or models of theory) are the theoretical predictions which, in the end, are compared to the results of the measurements. On the data path, one begins with the actual experimental setup. The essence of this process is that the measurement data (generated by the experiment) cannot be directly compared to the theoretical predictions. To make the comparison, the data must be transformed so that they form a 'model of the data' (Darling 2002).

For Duhem (1914/1954), the experimental results, the measurement itself and the instrumentation used in the measurements are all of central importance. Consequently, Duhem begins with experiments and introduces a sequence of 'translations' which transform experimental results into a form that theory can ultimately annex. The essence of Duhem's viewpoint is that the theoretical interpretation of the use of instruments and how they function is indispensable in every step of the translation sequence; the whole process of interpretation requires a number of theoretical propositions (Darling 2002). Yet, both employ a sequence of modelling steps needed to narrow the gap between actual measurements and the theoretical predictions; there is a mutual fitting of theoretical models to empirical results, as well as models of empirical results to theoretical models. Moreover, in the latter, not only are results idealised, but the experiments themselves are often altered, as is the manner in which the phenomena are produced.

The fourth notion summarises the role of simulative modelling by reiterating the notion of models as instruments (Morrison 1999; Morrison and Morgan 1999) and clarifying what it means to be a 'computational instrument of investigation'. These models emerge in the same cyclical process, where they serve as creative tools: Models bridge the experimental and theoretical world, because they embody both empirical and theoretical arguments in the modelling process. Simulations then serve as a tool for inferring relevant knowledge of the system and its emergent properties. Similarly, in Nersessian's (2002, 2008) view, the most valuable aspect of constructive modelling is that it provides cognitive means for simulative reasoning, mentally exploring or simulating the consequences of the model assumptions. Here, this capability of mental reasoning and simulating takes on a more formal appearance, as algorithmic simulation with the intent to reason and unfold dynamically the consequences of the model's assumptions.

The above four notions clarify the usage and development of models, what models are and how they relate to observable aspects of reality and theory. They also help to characterise the concept of 'model', which should be sufficient for practical purposes, but without attempting to define them. Several reasons compel one to resist the temptation to 'define' models; attempts to do so have turned out to be too restrictive in describing actual modelling practices. Rather than clear-cut definable objects in the philosophy of science, models are cognitive and pragmatic tools for exploring, understanding and manipulating the world with the purpose of constructing knowledge; they are undefinable, but understandable through the ways in which they serve these purposes.

However, an important question remains: How are models developed in the form of simulation models, which can be run in the virtual world of computers? In this we meet the technological limits and especially the idea of the computability, which Humphreys (2004) discusses extensively and in depth. When a model is implemented in a computer, it is simplified and rewritten in a form the computer can handle. Humphreys makes these ideas more transparent at the methodological level by suggesting that in simulations, one should distinguish between the *computational model*, *computational template* and *correction set* to the template. In Humphreys's scheme, the computational model is the model run in the computer, which is constructed on the basis of computational template. These computational templates are mathematical structures, such as formulas, which can serve fruitfully in different contexts; they are well known, and familiar moulds void enough content that they carry over to new unfamiliar fields of inquiry, but with the assurance of how they will work. In many cases, templates as such are insufficient and they must be augmented with correction sets. The correction set serves to match the simulation to the experimental process, thus allowing one to better pursue selectively realistic representations.

On the one hand, in this picture, the models are considered reliable, accurate and correct, but on the other hand, the model may contain sub-models in the form of local parametric models and parametric relationships which must – in a strictly realistic sense – have a direct counterpart in real systems. This, however, does not compromise the reliability of the models, nor does it mean that the models do not represent at all, because the purpose was to represent the real system only to a predetermined degree of realism. Already from the beginning, several possibilities to make the model more realistic are always known, but the increased degree of realism is nearly always sacrificed for the sake of the transparency of the pertinent phenomena, for the greater ease of its mathematical handling and, finally, for better computational tractability. Such a position is well described as selective realist (Humphreys 2004) or moderate realist (Koponen 2007).

The question of which follows is the one of how such selectively realistic simulations provide access to reality. To access real systems in practice, it is enough that they be controllable and manipulable and that new similar systems can be designed with desired features. This goal is realised through simulative modelling, which serves as an inference tool for producing instrumentally reliable models. First, by producing instrumentally reliable models, simulations help to isolate suitable real systems and phenomena to which these models apply. Second, through the bidirectionality of modelling and experimentation, simulative modelling provides a means to manipulate these systems through model predictions. Third, through these steps, simulations provide access to the real, as a means of manipulating and intervening, and for all practical purposes, it is here that the conceptual meets the real.

Thus far, we have discussed generative modelling on the basis of theoretical studies to understand what these ideas mean in the practice of knowledge building. It is now time to consider some examples drawn from practitioners' use of models and modelling.

35.5 Authenticity of Generative Modelling

The picture of the generative modelling painted here differs substantially not only from theory-subordinated verificative modelling but also from the strong realist position, where models' similarity to real systems is extremely important. Finally, this picture challenges the claim that the realistic position grants the authenticity. Of course, we must now respond to this challenge of authenticity and discuss the empirical evidence to support the views promoted here. We did this by exploring the modelling practices and practitioners working in the rapidly developing field of condensed matter physics. We interviewed (altogether ten) PhDs (apprentices, A) and more senior researchers (experts, E) about their knowledge-building practices through modelling (Tala 2011). This in-depth study will reveal clearly a stance of selective realism. The notion that the modelling topics studied are for systems in material sciences strengthens the weight of the argument put forward.

The interviewees' modelling activity focuses on understanding the nanoscale phenomenon through 'hands-on' manipulation of the various models by means of simulations. As one of the informants mentioned:

N1: our simulations are quite down-to-earth, but at the same time [they] make it possible to study general phenomena. (E)[14]

Such bi-directionality is at the core of the generative modelling; models can serve a twofold function: to improve both our understanding of a phenomenon in particular experimental settings and our understanding of the phenomenon on a more general level. Achieving such understanding also plays a role in the generic mental modelling that guides experts' problem solving in new situations (cf. Nersessian 1995):

N2: when beginning to simulate something new, we have often noted with happiness that we have already learnt this [kind of phenomenon] with metals. (E)

Selective realism is evident in many of model builders' comments; in comparisons of experimentation and modelling, only part of the models' features is selected. One interviewed expert explained what makes the models he develops valuable:

N3: In a certain way, in some cases the model is workable/usable for estimating certain things… What makes it interesting is that we can take into account certain important aspects – or the simplicity. (E)

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[14] Nine interviews were in Finnish, and one in English; the authors translated the excerpts.

In following excerpts, a couple of younger researchers explain further:

N4: The whole of molecular dynamics, would not function if the frequently repeated calculations were not made as simple as possible and quick for the computer to calculate. (A)

N5: If it [the model] becomes too complicated, it is no longer intuitively clear. I am looking for an intuitively clear model which includes the essential [features of] processes and little else. (A)

N6: The models used to represent different viewpoints of the same phenomenon need not be consistent with each other. Nor do even the parallel models need be commensurable. (A)

Modelling thus captures the partial similarity between the dynamic of the model and the respective part of the laboratory phenomenon under consideration. These remarks suggest that the mimetic similarity of models and real systems is reached through a selective realistic attitude towards models and modelling; only part of the systems' behaviour was of interest in one modelling process.

Modellers' views also contain information about how they see models as autonomous instruments of thinking and exploration, sufficiently free from theory to relax some of its constraints, yet sufficiently close to theory to adhere to the modelling assumptions based on sound physical reasoning and a theoretically motivated basis; all aspects need derive from theory, but they do need to be acceptable and make sense from the viewpoint of the theory. As tools of thinking, models are semi-autonomous constructs that function in the conceptual or virtual world and allow one to explore theoretical possibilities. Note that this would be impossible if models were deduced and derived from theory; then, nothing new would come out of modelling. Moreover, if the connection to theory is thin, it would be impossible to say which aspect of the theory is explored and how the model helps to increase knowledge. The interviewees described several examples of how playing in the virtual world provides them opportunity to construct and study systems with properties which may not be (or at least are not yet known to be) real, but could be real within the given theory. Sometimes such systems extremely reduced or idealised, and when needed, even contradict some theoretical principles. Modellers also highlighted this autonomous role at the general level:

N7: A model lives its own life. (E)

Such remarks are typical among physicists. Indeed, they are unmistaken signs of the semi-autonomous use of models as tools of thinking and knowledge construction.

The modellers' conceptions of the ways in which the models mediate between theory and experiment also typically fall in selective realism and instrumental use of models. As three experts put it:

N8: Basically, what my experimental colleagues give me — as an example — Could you please explain why it [an experimental result] is like that. Not simply to explain, but sometimes [to support] a proof of why this [result] can be used as an effective rule for the construction of some materials and not others…. Not simply to explain, but also to understand. (E)

N9: It's very common that a theory creates reality in the sense that modellers propose some sort of explanation for phenomena, not necessarily only for this one, but a general one. (E)

N10: It is a model which explains a particular physical phenomenon. And then everyone follows that model. The model is probably fine and correct, and sometimes it is not. But experimenters start thinking in terms proposed by this'theory'. (E)

Thus, the experimenters need a model to plan the experiment and to interpret the data obtained from it. Some responses also mentioned that, at best:

N11: the simulation predicts something that will be found out through experimentation in the future. (E, A)

The modellers also described how they:

N12: develop new ideas and try them out [in the virtual world] to see which ones are worth testing in experiments. (A)

N13: discuss with the experimenter what can be done and what should be done. (E)

Such developments and discussions are conducted before launching a new research project. Both particular models and particular experiments can thus be more or less purpose-built to each other already from the beginning.

The interviewees also described how the computer model and experiment then become more closely fitted in the cyclic, iterative processes in which running the simulation plays a central role in understanding and developing both the model and the experimental process. Such a modelling process employs many sources of knowledge. In addition to available experimental data available or theoretical calculations, the interviewees compared simulations with other simulations and simulation results and employs practical knowledge:

N14: Everything available; even plain hand waiving in situations where we do not know what exactly is taking place. (E)

Naturally, these 'hand-waving explanations' are educated guesses based on scientists' experience in modelling practices and their understanding of the principles underlining physics. Referring to the origin of such constructive knowledge building, one expert noted:

N15: We should not forget that we are studying mental projections; we study mental pictures which are foundationally mental. It is what we see. (E)

In the interviews, instrumental reliability is most often about computational or algorithmic reliability or functionality. The capability of models to mediate, on the other hand, rests heavily on such instrumental reliability.

N16: A model doesn't care about the actual conditions or claims to explain them, since the only important property of a model is its functionality. (A)

In fact, the ideas expressed by the modellers are very close to the views what Humphreys has discussed under the rubric 'the template', meaning an established and shared algorithmic or computational structure. As the following response puts it,

N17: Simplified mathematical gizmos are the elements shared by the different models. (A)

N18: The harmonic oscillator is the most generally used model in physics; it is used nearly everywhere…. After all, nearly all interactions in these simulations are modelled by harmonic potential. (A)

N19: When a physical template is fitted to a computer, it becomes a kind of new theory… Owing to the digital nature of computers, the discretised template – which is the physical model fitted in the computer – is never the same as the original physical template which provided the starting point. (E)

The choice of 'simplified mathematical gizmos' (see N17) is justified by its tractability and ease of use:

N20: This mathematical model is used because it is computationally very undemanding and effective, … these models are naturally quite simple, and thus do not represent a system very well. (A)

Here, again selective realism is the unmistaken underpinning of the attitude towards modelling; the practical limitations of simulative modelling override even the desire for realism. And finally, what is achieved is an instrumentally reliable and functional model as well as knowledge about its functions. Moreover, the interviewed scientists frequently refer to practical values; a new model is good if it operates as intended, namely, if it produces the events observed in experiments or predicted by more general theoretical models.

Models and their simulation serve as valuable tools in the creative work of scientific knowledge building. They embody both theoretical and empirical ideas developed in the flexible virtual world. It is quite natural that only semi-autonomous models would be able to serve as an instrument. Few remarks refer to these aspects, but remarks N7 and N14–N17 do. Indeed, we noted that experienced modellers perceive the semi-autonomic role of models as a more covering aspect than novices do; understanding this autonomy seems to be characteristic of the expert-like approach.

The semi-autonomy of models is linked to the fact that scientists favour the functionality and computability of the models and selective realism over strict realism. Consequently, although the interviewees wield the models with a substantial, well-articulated theoretical knowledge, they are not mere deductions from the theoretical structures, nor are they deduced or induced from experimental results; rather, they are rich physical constructs which mediate between theory and experiment. Indeed, the bi-directionality of the model with the adjustments based on empirical evidence, coupled with the usage of the model as a tool for investigation – in the spirit of selective realism or weak realism – seems to be an obvious perspective for modelling practitioners working in many fields of physics. The picture that emerges from the practitioners' views lends little support to a strong realistic stance on modelling, or modelling seen as an essentially theory-driven endeavour. Rather, the picture contains many elements discussed here under the rubric of generative modelling, with a selective realistic position emphasising the instrumental use of models, and sees models as semi-autonomous, mediating tools of reasoning and thinking.

35.6 Implications for Physics Education

The generative modelling in physics could promote a more authentic view of models and modelling than the more traditional picture of modelling based on a strong realistic position with its emphasis on prediction and explanation. In short, we suggest that the models and modelling should not be introduced only as tools for explaining scientific content, but also as instruments for creative thinking with the purpose of creating scientific knowledge. In education that takes this notion into account, the points to be highlighted are (1) mimetic similarity, (2) instrumentally reliable models that are sufficient with very moderate realism, (3) generative modelling that mediates between theory and experimentation as an independent approach and (4) generative modelling that is an instrument of creative investigation. In implementing this generative perspective of modelling in science teaching, it is natural to use the research-based resources for science learning and teaching that we already have. For example, cognitive demands must be taken into account in planning, which means that such an approach is not easily adapted to preliminary levels of science learning. It becomes accessible perhaps in upper secondary school level, desirable in the first year at the university level, necessary at the end of advanced studies and, finally, indispensable at the expert level, where the role of generative modelling is easiest to see in new fields of research. Modelling in contemporary physics is still quite a challenging theme, even for teachers, and even more so in the current situation where implementing theory-derived and more straightforward modelling approaches into education is still relatively new.

One very clear requirement of generative modelling activity is that it should be a dynamic and generative activity that produces (processual) mimetic similarity with phenomena or with processes occurring in real world. At the practical level, this means that model relationships are couched in terms of changes and differences, technically as difference equations or differential equations with constraints. At a more untraditional level, the dependencies and interactions in model elements and their relationships come in the form of updating rules for states of the model, as in cellular automata or in agent-based models. Such models have no direct one-to-one relationship with the system that could be studied with the model and where one could assess the similarity of the system and model. In high school-level teaching and in undergraduate teaching, generative and simulative modelling means that more attention should focus on how certain kinds of dependencies of the model level generate certain dynamic behaviours in the simulation run. For example, what kind of motion is related to linear restoring forces, to inverse power law forces or to exponentially decreasing forces, how do these types of forces act in combinations, and what features of generic behaviour one can detect in real phenomena? Such a model-based approach in practice is quite similar to approaches suggested by Halloun (2007) and Nersessian (1995). In Halloun's and Nersessian's suggestions for perceiving modelling, the goal is to understand the generic mechanism behind the most important features of the phenomena. In this sense, simulative modelling through its capability to provide mimetic similarity provides new tools and new ways of thinking about how to see the world and how to make sense of its regular features. There is also considerable room for one's own invention and construction of models. Such objectives, implicated by the generative nature of scientific modelling, are unattainable with modelling that is too simplified. Indeed, the success of practical solutions requires sufficient domain knowledge (Nersessian 1995). Thus the difficulty of the suggested content of such examples of generative modelling makes implementing these ideas challenging at the lower levels of education.

Moreover, using the models as tools for creative thinking and the construction of knowledge can be challenging in the tradition of science education that emphasises realistic views of models and modelling and where the visual similarity of a model to the target system or the quantitative agreement of model predictions with a measured property of the system is of greater importance. The integration of mathematical or IT modelling lessons with modelling in physics could provide a natural place to introduce new perspectives. In mathematics and IT lessons, students may engage more easily in studying the dynamics of models and modelling in the virtual or mathematical world without striving for a direct one-to-one relationship with the physical world, thus enjoying more freedom to explore theoretical ideas. Practising scientists enjoy such freedom, so why not permit the same freedom and joy of invention in teaching and schooling. The role of mathematics in physics is then perceived as essential means to create and develop physical ideas, where mathematical structures themselves can provide new ideas, rather than of seeing mathematics only as a technical tool for making calculations (or, as sometimes seems to be the case, a nuisance which prevents the capture of the true 'conceptual understanding'). Furthermore, emphasising generative modelling may encourage the effective and efficient reorganisation and employment of mathematics in physics lessons, not as a rival to empirical activities, but as a natural counterpart on a par with experimentation – as it is in doing science.

Teachers' views strongly affect the ways in which models and modelling are used in practice in education, which then affects students' views of physics and learning physics. Therefore, generative modelling should be discussed not only in the education of experts in modelling but also in science teacher education. One obvious way to address generative modelling is to use examples drawn from practice (as in Sect 35.5 here) to show that models and modelling can serve not only as a means to demonstrate achieved and agreed consensus on scientific ideas but also as thinking tools in the construction of scientific knowledge, as well as justification strategies in discourse. Even if students have insufficient background knowledge in physics and mathematics to engage in generative modelling, in many cases they can follow the ideas behind a generative modelling process when it is reconstructed and discussed. Reconstructing such examples of a modelling process and how it relates to empirical evidence can serve in science teaching as well as, for example, reconstructed scientific historical examples. Students can also participate in the shared construction and development of a model by creating analogies and forming idealisation and generic abstractions. Indeed, in creative activities, teachers should be able to understand different ways of thinking (cf. Blum and Ferri 2009) when supporting students in constructing and developing ideas in modelling.

In summary, if we want school science to reflect useful and fruitful aspects of modelling in physics, we should focus much more to new types of creative, generative and simulative modelling. Instead of trying to show how models are produced and refined by relying on established theory, we should be able to show how to produce interesting and suggestive new models and how they can guide generation of new theoretical insights and guide us in seeking new empirical regularities in phenomena. Of course, because the more traditional modelling entails many similar steps, what has been said of this type of modelling remains valid and is not overturned.

35.7 Conclusion

The notions of simulative modelling discussed here call attention to several aspects of modelling one must take into account in producing modelling activities for teaching purposes. First, the essential part of modelling is its close relationship with experiments and experimentation: Models are mediators between the conceptual and the real and serve as means of intervention and inference. This means that in teaching solutions, we should carry out parallel and mutually supportive activities of modelling and experimentation. Second, in developing models, theory is not the only starting point of modelling. Rather, model development requires a variety of sources: theoretical, empirical and computational. The practice and purpose of modelling guides how these sources can be used and employed. This leaves much room for the creativity of modelling and also emphasises the constructive and cognitive aspects of modelling, fitting well constructively oriented teaching that supports students' own knowledge construction. Transferring the mathematical models between different fields of physics in modelling also provides room for understanding the role of mathematical thinking and reasoning in physics. Third, and finally, simulative modelling enhances the view that much of science involves not so much of finding the fundamental truths of nature, but rather constructing reliable and functional knowledge which can help us to cope with nature.

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Chapter 36
Models in Science and in Learning Science: Focusing Scientific Practice on Sense-making

Cynthia Passmore*, Julia Svoboda Gouvea*, and Ronald Giere

36.1 Introduction

Over the last few decades, there has been a “practice turn” in the philosophy of science and, more recently, in science education. That is, there has emerged in both fields an effort to understand and apply ideas about how science is actually practiced to issues in philosophy and education.[1]

What this practice turn has meant is that philosophers, along with other scholars in science studies, have turned from seeking an account of science as a singular, logical system for knowledge generation and evaluation and instead have begun to focus more carefully on an examination of the nuances and context dependencies of what scientists actually do to further their aims of making sense of the world. This turn has been described as naturalistic or pragmatic, because it abandons some of the assumptions and constraints of a more traditional philosophical approach in favor of a more empirically based one and, in this way, offers more authentic descriptions of the scientific endeavor.

Similarly, in science education, there has been much debate and discussion about the distorted and decontextualized version of science that has come to be known as “school science.”[2] There is an emerging consensus that the overarching emphasis on a singular “scientific method” combined with a focus on memorization and test

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*Note: The first two authors contributed equally to the creation of this manuscript.

[1] See, for example, Giere (1988), Nersessian (1992, 1999, 2002), Morrison and Morgan (1999) from philosophy of science and Duschl (2008), Gilbert (2004), Matthews (1992), Osborne et al. (2003), and Hodson (1992) from science education.

[2] See Duschl (2008), Hodson (1996, 2008), Rudolph (2005), and Windschitl et al. (2008b).

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preparation has contributed to a crisis in science education. Many able students are turning away from science, and more worrisome, there is an alarming lack of scientific literacy among the general public (e.g., Bauer 1992). The practice turn in science education, like the turn in the philosophy of science, has manifested itself in calls for science learning environments to become more authentic to science as actually practiced.

There are two primary reasons to situate science education reform in a consideration of scientific practice. The first is that by engaging students—in explicit ways—with a version of school science that is authentic, students may emerge with a more accurate view of the scientific enterprise. Having such a view will be useful to students as they consider new advances in science and in making decisions about their own futures. Second, because there is a great deal of alignment between how scientists think and reason and the powerful learning mechanisms that all humans use to navigate the world, engaging students in contexts that are authentic should produce a deeper understanding of and insight into the content of science. Indeed, there is good reason to believe that these two aims can be achieved with science education that has been carefully crafted to be authentic.[3]

Meeting these goals requires developing learning environments that engage students in intellectual work that mirrors the work that scientists actually do. And, this means having a clear and coherent picture of the scientific enterprise, one that is developed by looking closely at how science is actually practiced with an eye to how that work can be productively *translated and enacted* in an educational context.

Thus, the practice turns in both science studies and in science education have parallel aims, to attend to the authentic nature of science as it is actually practiced, as well as a parallel challenge, to make sense of the messy intellectual endeavor so that some coherent understanding of the scientific enterprise can be described. Scholars in science studies have examined the complexity of scientific practice from a range of perspectives. Authors have focused on the social structure of science, the cultural and epistemological norms, the day-to-day practices and routines of scientists, the role of tools and material forms, and the reasoning and problem-solving strategies used in scientific practice. Given the nuances and complexities of scientific practice, it can be difficult to conceive of how it can inform the design of science learning environments without leaving us with an account of science that is so diffuse and unstructured to be of practical use.

One way to address the complexity problem is to emphasize the cognitive endeavor of science by focusing on the practice of science and how it supports making sense of how the world works. Such a view does not ignore other perspectives; as Giere and Nersessian have argued, scientific cognition is necessarily embedded in sociocultural contexts where it is shaped and supported by complex interactions with other humans and with material forms. However, a focus on cognition can provide one clear avenue for translating scientific practice into science classrooms.

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[3] See, for example, Stewart et al. (2005), Duschl (2008), Engle and Conant (2002), Ford (2008), Duschl and Grandy (2008), Lehrer and Schauble (2004), and Roth and Roychoudhury (1993).

This account makes supporting sensemaking primary and asks how can the social, cultural, and material aspects of science classrooms can be structured so that scientific reasoning is supported. It is from this starting point—that a central aim of science education is to engage students in scientific sense-making—that we move forward with for this chapter.

Increasingly, scholars in the history and philosophy of science have turned to examining the pivotal role that models and modeling play in organizing the cognitive activities of practicing scientists. A recognition of the importance of models and modeling in science education has been on the rise as well. There are important connections to be made between the science studies efforts and those in science education around the centrality of models and modeling in the practice of science. A careful consideration of the nature and use of models in science can provide one way to organize our understanding of scientific practice and frame the way we translate this practice into science classrooms to support meaningful sense-making.

36.1.1 Driving Question and Overview

In this chapter we will examine how historians, philosophers, and psychologists have viewed the role of models in science. In particular we are interested in how models function as reasoning tools that allow one to bound, explore, organize, and investigate phenomena and to develop explanations, generalizations, abstractions, and causal claims about those phenomena. We hope to draw out the nature and function of models as context-dependent tools that productively organize a range of sense-making work that scientists undertake in their practice. Sections 36.1 and 36.2 of this chapter are intended to answer a particular driving question:

How do models function to structure and organize scientific practice around sense-making?

To address this question, we first present a rationale for focusing on models; then address ontological and epistemological questions about the nature, form, and development of models; and finally examine how models are actually used in scientific practice.

Ultimately, our goal with this chapter is to unify the views from the science studies literature on how models operate in scientific work and to explore the implications of this view for science education. In order for learning environments to reflect authentic science, they need to be designed to mirror the cognitive activities of scientists. In Sect. 36.3, we address the question:

How can a model-based view of scientific practice be leveraged to organize and focus classroom activity in support of sense-making?

To address this question, we propose a framework for organizing ideas about model functions in science education and apply that framework to a collection of studies in the science education literature. The chapter ends with a consideration of a number of practical and theoretical implications and recommendations.

36.1.2 Rationale for Model Focus: "Why Models?"

To begin, we briefly examine work in history and philosophy of science that motivates our examination of models in science and science education. Much of this scholarship draws on Giere's seminal work in this area, *Explaining Science*. In it he made a deliberate turn away from the "general program" in philosophy of science to a more naturalistic one that examined how scientists actually go about their work on a cognitive level. He began with the assumption that "the representations that scientists construct cannot be radically different in nature from those employed by humans in general" (Giere 1988, p. 62); that is, the sense-making apparatus common to all humans is at work in science as well. The layperson's mental model is not different in kind from the widely accepted scientific model; rather, scientific models are more carefully constructed and systematically evaluated extensions of a more basic cognitive strategy.

This turn toward understanding the meaning making that scientists, as humans, do, rather than characterizing the products of their work on a structural level, emerged from what became "the cognitive study of science," in which mental models play a central role. There was a historically parallel, but independent, move in the philosophy of science from a "syntactic" to a "semantic" view of scientific theories. The latter moves beyond the abstract structure of theories to include issues of the meaning of scientific terms and the truth of scientific statements. In the semantic view of theories, models, still understood as logical rather than mental constructs, are central. Melding these two traditions has been a complicated process (see Downes 1992; Knuuttila 2005). Neither tracking these historical developments nor analyzing their various commitments is our intent here as this has been skillfully done in a number of recent papers for the science education audience.[4] For our purposes, the significance of these developments is that they gave prominence to the idea that models play a central role in scientific sense-making. Fully unpacking why a focus on models in science is useful and how models operate in scientific sense-making requires moving beyond purely philosophical concerns and bringing together a more integrated science studies approach that combines cognitive-historical, psychological, and ethnographic methods.

For example, over the past 15 years, Nancy Nersessian and her colleagues have undertaken a psychological approach to studies of actual scientific practice using both cognitive-historical and contemporary ethnographic techniques. They have spent years observing, documenting, and talking to scientists as they do their day-to-day work (e.g., Osbeck et al. 2010). From these studies has emerged a clear sense that models are at the center of the day-to-day work of science; they are the functional units of scientific thought. As Nersessian explains, mental modeling is the underlying cognitive machinery that makes model-based reasoning so fundamental

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[4] See Adúriz-Bravo (2012), Bottcher (2010), (Develaki 2007), and Koponen (2007 and this volume). Please also see a special issue of *Science & Education* (Matthews 2007) for a careful treatment of models and modeling for the education audience.

to human sense-making. It is the general machinery that underlies our ability to engage in the more formalized scientific strategies of generating representations, using analogies and thought experimentation.

Building on the foundational works of Giere and Nersessian, there has been a proliferation of scholarship in science studies related to uncovering the role of models in science. For example, Morgan and Morrison (1999), in their edited volume, *Models as Mediators*, pulled together a range of articles that explored the ways in which models function in a variety of disciplinary contexts. And, numerous other scholars situated in biology, chemistry, physics, and economics have undertaken both historical and contemporary descriptions of model use in science.[5] Similarly, in the science education community, there is an emerging movement that acknowledges models and modeling as important aspects of scientific practice (e.g., NRC 2011; Windschitl et al. 2008b). Taken together, these studies provide a rationale for organizing science instruction around models and the primary motivation for this chapter: Models are central to scientific sense-making. They provide a way to organize our understanding of scientific practices and a way to understand the purpose of scientific activity.

Alternative organizing frameworks that centralize other aspects of scientific practice are certainly possible. To focus on models is a choice that, as we explore in this chapter, has particular affordances. Specifically, an explicit focus on modeling helps organize scientific practices such as representation, experimentation, and argumentation around the purpose of making sense of phenomena rather than as discrete activities. Although, this unification is seamless in actual scientific practice, in science education, unification can be more challenging. In the next section we draw on science studies to support the claim that models are central to the sense-making practices of scientists and examine the implications for science education.

36.2 Models in Scientific Practice and Science Learning

This section builds toward an understanding of models as context-dependent tools for making sense of phenomena by drawing on the work of philosophers and historians who emphasize the functional role of models in science. First, we address ontological questions about the nature and form of models, we then address epistemological concerns related to model construction and evaluation, and finally, we turn to a functional account of how models are used in scientific practice. What emerges from this account is a definition of models that emphasizes their utility as tools for sense-making as well as a description of the specific ways in which models

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[5] In biology, see Cooper (2003), Lloyd (1997), and Odenbaugh (2005, 2009); in chemistry see Suckling et al. (1980); in physics see Cartwright (1997, 1999), Hughes (1999), and Nersessian (1999, 2002); in economics see Boumans (1999) and Morrison (1999). See also Auyang (1998) for comparison across biology, physics, and economics.

serve this function in science. This view of models, embedded in scientific practice, can provide a productive framework for organizing science education environments which is the focus of Sect. 36.3.

36.2.1 What Are Models? Ontological Concerns

> Few terms are used in popular and scientific discourse more promiscuously than "model." (Nelson Goodman 1976, p. 171, as cited in Odenbaugh 2009)

It can be challenging to define models in a concise way. Nevertheless, drawing on pragmatist philosophers, we identify several key attributes of scientific models:

1. *Models are defined by the context of their use.*
2. *Models are partial renderings of phenomena.*
3. *Models are distinct from the representational forms they take.*

In this section we discuss each of these features and discuss the implications of this definition of scientific models for education.

36.2.1.1 Models Are Defined by the Context of Their Use

Nersessian (2002) refers to the cognitive processes involved in deciding how to construct a model as mental modeling. Note that she makes a distinction between mental models, often described as knowledge structures stored in the long-term memory, and mental model*ing* as a *process* of human sense-making. We take up the latter view of model-based cognition as a flexible, context-dependent process whereby humans interpret and reason about situations by selecting and drawing together cognitive resources. Conceived of in this way, models are dynamic entities that are constructed and used as needed.

Although the word model is used to describe a wide range of entities in the sciences, one cannot actually provide a clear definition of what is and is not a model in an abstract sense. As Teller states:

> The point is that when people demand a general account of models, an account which will tell us when something is a model, their demand can be heard as a demand for those intrinsic features of an object which make it a model. But there are no such features. WE make something into a model by determining to use it to represent. (Teller 2001, p. 397, emphasis in original)

For these reasons we fall back on a very basic framework for a model, that models are sets of ideas about how some aspect of the world works. Models are entities that represent some aspects of a phenomenon to some degree. But which of those aspects and to what degree will not be uniform across contexts. Thus, while some philosophers have attempted to specify this relationship as an isomorphism between some source (the world) and some target (the model), we use the more relaxed

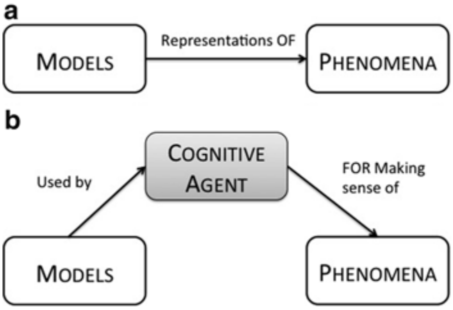

Fig. 36.1 From a dyadic to a triadic understanding of the relationship between models and phenomena. (**a**) The dyadic model focuses on defining the relationship between the model and some phenomenon. (**b**) The triadic model reframes the problem by shifting the focus to the cognitive agent who will ultimately be responsible for determining the nature of the relationship between the model and the phenomenon in a way that is useful given a particular aim

criterion of *similarity* (Giere 1988) to describe the relationship between models and phenomena. A slightly more precise version of the similarity criterion is proposed by Teller who describes similarity in terms of properties: Systems have properties, and some of these (depending on the objective of the modeler) will be part of the model (2001, p. 399).

Perhaps more important than defining what a model is defining what it is not. Appealing to similarity does not imply that any object that is similar to a natural phenomenon is a model. A globe, for example, is not a model of the Earth by default. It *becomes* a model when it is used to make sense of some puzzling pattern or answer some question. The same object can both be a model and not be a model depending on how it is being used.

Pragmatist philosophers, beginning with Giere (1988), have argued that the relationship between models and the world only makes sense in the context of their intended use *by some cognitive agent*. In defining models we cannot simply consider how the model relates to the phenomenon it represents; we must explicitly consider the role played by the cognitive agent (see Fig. 36.1, Giere 2004; Knuuttila 2005). By explicitly drawing attention to the cognitive agent in the system, we end up with a definition of models that foregrounds their function in reasoning. It is the cognitive agent, the modeler, who will decide how to bound, filter, simplify, and represent the phenomenon to generate a model. Which features need be shared and to what degree will depend on the way in which the model user wants to understand that phenomenon.

36.2.1.2 Models Are Partial Renderings of Phenomena

Understanding models in terms of their use can also help clarify the relationship between models and real-world phenomena. It is common to see models referred to as abstractions, simplifications, idealizations, or simply representations of phenomena. Specifying the exact nature of the relationship between models and the world has been a central point of debate in the philosophy of science literature (Downes 1992; Knuttila 2005). As Downes describes, the motivation for this debate has been to say something philosophically robust about models as knowledge structures—to answer the question what can models really tell us about the world? Many proponents of the semantic view have attempted to define the relationship between models and the world as isomorphic. However, for Downes and other pragmatists, the attempt to define a singular relationship between models and real-world phenomena misses the mark. Neither an account of models that focuses exclusively on isomorphism nor an account of models as purely analogical nor any other general account will apply in a universal sense to the variety of different kinds of scientific models that have been historically and continue to be used by practicing scientists (Downes 1992).

Cartwright (1999) similarly challenges the notion that phenomena can be mapped to general theories. Instead, she acknowledges that different phenomena may require models, which vary in the degree to which they make different simplifying assumptions. Cartwright's account is a rejection of the universalism of laws and an acknowledgement of the diversity of phenomena themselves, each of which require its own model formulation. Cartwright describes how a coin dropped from a height can perhaps reasonably be modeled using a simple Newtonian model. But the same model cannot help account for the motion of a dollar bill. The result is that reality is covered by a "patchwork" of models (see Fig. 36.2). This metaphor begins to complicate the possibility that there is a single way to characterize the relationship between models and the world.

Rather than attempt to map a one-to-one relationship between models and phenomena, Morrison and Morgan (1999) describe models as "partial renderings" that can differ widely in the extent to which they accurately represent real systems. They describe how a model of a pendulum can be simple and abstract when used as a means of making sense of simple harmonic motion but can be refined with a series of corrections that increase the complexity of the model as well as its success in making accurate predictions. There is no singular model of a pendulum; rather there are a group of overlapping models of a pendulum, each of which can be used to reason about a pendulum in a different way.

When the importance of a cognitive agent is recognized, a better metaphor for the relationship between models and phenomena is a geometric one proposed by Auyang (1998). As Auyang describes, attempts to a define a one-to-one correspondence between the world and our theoretical understanding of it necessitate a *finite geometry* in which our understanding maps onto the world like "a single global coordinate system covers an entire manifold" (1998, p. 74). As an alternative, Auyang proposes we think of science in terms of a *differential geometry,* in which the manifold is covered by overlapping local coordinate systems (see Fig. 36.2). Thus, Cartwright's patchwork is best understood not as a regular quilt with patches stitched together to create a complete understanding. Instead, the patchwork is much more irregular, with patches of different sizes and shapes overlapping with

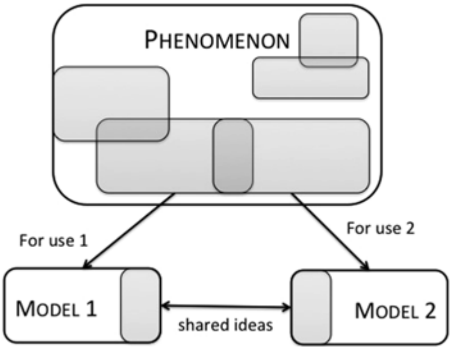

Fig. 36.2 Models related to phenomenon by an overlapping patchwork each of which is used for a slightly different purpose and makes different features of the phenomenon salient to the modeler (After Auyang 1998). *Grey boxes* represent different aspects of some phenomenon that a modeler has chosen to focus on for some particular use

one another, creating areas with many layers of coverage and possibly other areas with large gaps. It is the model user who decides which patch to apply to the world, depending on her aim.[6]

36.2.2 Models Are Distinct from the Representational Forms They Take

Just as there are potentially multiple models that can be used to make sense of a phenomenon, there are also multiple representational modes that any given model can take. Knuuttila (2005) describes modeling as involving two levels of representation. The first level involves choosing the attributes of the system that are relevant to include in a model. Such choices are dependent on the aim of the modeler as noted above. The second level involves making a choice about *how* to represent the relevant attributes of the system in some material form. Often these two levels cannot be separated—choices about what features are important will suggest a particular form just as the choice of a material form will afford or constrain what is attended to. Nevertheless it is worth pointing out that essentially the same ideas can be conveyed in a variety of representational modes including diagrams, equations, physical models, or written text. These different forms should not be conceived as different models per se; rather one should focus on the differences in representational mode.

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[6] There are two recent books that develop the "patchwork" idea in quite rich directions for those readers who might want an even more sophisticated version of these ideas: Mark Wilson, *Wandering Significance*, Oxford Univ Press, 2006, and William Wimsatt, *Re-engineering philosophy for limited beings*, Harvard Univ Press, 2007.

Too great a focus on the material form of a model can be problematic because it tends to collapse the triadic relationship (between model, cognitive agent, and phenomenon) back into a dyadic one (model and phenomenon only) (see Fig. 36.1). A diagram of the cell is referred to as a "model *of* the cell," but this diagram by itself is merely a depiction of a physical object because it does not suggest what such a diagram is good *for*. Thus, despite the widespread usage in education circles of the word model as applied exclusively to physical objects (like Watson and Crick's tin and cardboard DNA molecule), it is not the material aspect or embodiment of the object that makes it into a model.

In the DNA example, the physical object was deployed to figure out something in the world; it was the physical manifestation of the key features of DNA that were relevant to understanding the mechanisms of inheritance. The material aspect of Watson and Crick's model was absolutely critical, but it was not the *materiality* that made it a model; rather it was how the abstract ideas about the structure and function of DNA along with Franklin's x-ray data were embodied in the material object and how it could then become a tool *for* reasoning about how the molecule functioned. The physical mode of representation was important because it allowed Watson and Crick to visualize precisely how the bond angles among atoms fit together and allowed them to feel confident that their structural understanding was correct. But, as the final line of their manuscript makes clear, that understanding was crucial for making sense of how DNA could possibly function in transmitting genetic information (Watson and Crick 1953).

To return to the of/for distinction made earlier, the three-dimensional structure of DNA is best understood not simply as a model *of* DNA but as a model that included the relevant structural elements of the molecule, thus allowing them to use it *for* developing a deeper understanding of its function. Educators tend to refer to the representational forms themselves as models (i.e., this is a 3-D model of DNA) rather than referring to representational systems as a whole (i.e., this is a physical representation of a DNA molecule that allows one to reason about how this molecule's structure relates to its function in biological inheritance). Unfortunately, this shorthand can promote confusion by foregrounding the form and backgrounding the intention. Being unclear about this issue can lead teachers to conclude that they are doing the scientific practice of modeling in their classrooms whenever they have their students working with physical objects. In fact, it is the cognitive activity—the sense-making—that should provide the primary criterion for determining if students are engaged in modeling. This kind of sense-making goes well beyond merely labeling parts and memorizing functions.

36.2.2.1 What Is a Model? Implications for Science Education

We can use this expanded understanding of models to gain some additional traction in defining models in science education: Models are not simply *of* phenomena, they are tools to be used *for* some reasoning about that phenomenon (Fig. 36.1). This distinction has important implications for decisions about what kinds of models to include in science curricula and for how we assess students' abilities as modelers.

A number of recent articles in the science education literature attempt to provide a typology of models in science toward a goal of finding a list that is inclusive and useful to educators for making decisions about what kinds of models to bring into science classrooms.[7] These typologies emphasize the importance of carefully considering the context when making decisions about the model form and content in instructional settings. However, one challenge of these lists is that they can be difficult to interpret on a philosophical level and use in science education because they do not distinguish models from their representational forms. For example, Harrison and Treagust (2000) present a typology that orders models from concrete scale models, through abstract theoretical models, to complex dynamic systems simulations. This ordering is meant to reflect conceptual demand; concrete scale models (e.g., a scale boat) are less challenging than process models (e.g., a chemical equation) and are therefore positioned lower in the typology (p. 219). Harrison and Treagust suggest a learning progression that first introduces students to concrete models and moves toward introducing more abstract models.

The general point that the models used in educational contexts must be chosen in accordance with the abilities of students is an important one but is made more clear when models and their representational forms are kept distinct. A scale model of a boat can be a less sophisticated reasoning tool than a chemical equation, but this has less to do with the representational form than it has to do with the ways in which the models are used. If the scale model of the boat is used to merely represent surface features of a boat, this is not very sophisticated, and indeed the cognitive demand may be relatively low. However, if the scale model of the boat is used to highlight how boat shape relates to buoyancy, then more intellectual challenge is introduced. A scalar representation *of* a boat is not a scientific model at all, whereas a scalar representation of a boat that can be used *for* reasoning about the phenomenon of floating by illustrating scientific ideas about displacement could be one way of representing a model for buoyancy. Thus, the cognitive demand of a particular model has less to do with the form it takes and more to do with the function it serves.

By defining models in the context of their use, the focus shifts to choosing a model that can be used to make sense of the target phenomenon in a way that is appropriate for the cognitive agent. This might mean that in some classroom contexts, a smaller set of constructs are introduced and simpler relationships are highlighted than are present in the model versions used in the scientific community. This point is made by Gilbert and colleagues in their discussion of curricular versus scientific models. Curricular models are simplified versions of scientific models that are specifically adapted for classroom use. Gilbert (2004) suggests that teachers must choose these curricular versions with an understanding of "the scope and limitations of each of these models: the purposes to which they can be put and the quality of the explanations to which they can give rise" (p. 126). That is, teachers and curriculum designers need to carefully select or construct versions of scientific models with which students can productively think.

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[7] See, for example, Boulter and Buckley (2000), Coll and Lajium (2011), Gilbert (2004), and Harrison and Treagust (2000).

Introducing a model into a classroom also includes, as Harrison and Treagust (2000) suggest, the need to consider the representational form. However, because of the dual nature of the representational role of models, two sets of questions about what kinds of models to introduce to students must be asked: First, with what set of ideas do we want students to engage, and second, what representational mode or modes can support interaction with those ideas?

It is important to separate the notion of the model from the particular representational form it takes. One reason for this has been to keep students focused on the success of the model as a reasoning tool as opposed to particular features of the representational form that can sometimes distract them from the salient conceptual elements of the model. For example, when first graders were asked to design a physical object that "works like an elbow," they tended to focus on the surface features of the representation, adding details to the models that had only to do with physical resemblance between their replicas and real elbows (Penner et al. 1997). Part of the reason they did so seems to be because the task was purely a representational task—make the elbow—and students responded by making physical replicas *of* elbows.

Imagine if the task had been rephrased so that it foregrounded a sense-making aim and backgrounded the representation, e.g., how is it that an elbow allows you to pick up something? This could have been done by introducing some flexibility in the choice of representational form instead of requiring students to build a physical model or by reframing the task around explanation as opposed to design. In such a scenario, the task would have been framed such that the purpose—to understand something about how elbows work—would have been highlighted. A follow-up study by Penner and colleagues demonstrates a shift in this direction where the students began to explore ideas about the elbow as a fulcrum, introducing ideas about torque and distance. In this second study, the model was no longer seen as one *of* the elbow, it was *for* understanding how lever systems like the elbow actually work (Penner et al. 1998).

The reason the *of/for* distinction is so powerful for education is that, again, it situates the model in the context of its use. It highlights function over form. In addition, it helps to keep the focus on reasoning and making sense *with* the model rather than reducing models to just another thing to be learned by rote in the science classroom. Models should be deployed in science classrooms as dynamic entities that help organize and focus a class of cognitive activities toward a clear sense-making goal.

The second major implication of defining models in terms of their intended use is that there is no single model of any particular object or system but rather many possible models, each of which has different affordances and constraints for reasoning about that phenomenon. In the science education literature, mental models are sometimes used to refer to static representations of students' ideas stored in long-term memory. Students are often described as having models "of" particular phenomena. For example, Gilbert (2004) states that "[a]ll students of chemistry must have a mental model, of some kind, of an 'atom,' all those of biology of a 'virus,' all those of physics of a 'current of electricity'" (p. 117). Often students are asked to externalize their internal mental models as drawings (e.g., Coll and Treagust 2003; Gobert 2005). We have seen this work interpreted to mean that students have a singular view of a particular entity or process with the implication that if this view is incorrect, it must be replaced with the correct consensus model.

Defining models in terms of their purpose allows for the possibility that students, like scientists, have multiple sets of ideas about scientific phenomena. The ideas students have about an atom are likely to vary depending on how they are being asked to think about atoms. For this reason it is important when asking students to generate models to be clear about the purpose of the activity. Asking students to depict a generic model (e.g., "Draw me your model of an atom.") is an underspecified task because it does not help them, as cognitive agents, make informed decisions about which features and relationships are important to represent. Consider the difference in the salient ideas that the student would need to draw on if she was trying to reason about bonding versus nuclear radiation.

If instead models are defined as sets of ideas that are activated in the working memory in response to a particular aim, we shift the focus from whether or not students possess a correct mental model to helping draw out the productive ideas that students have for making sense of particular phenomena. This can help orient educators to drawing out and building on students' ideas rather than attempting to replace misconceptions (c.f. Hammer 1996). Modeling in the science classroom has the potential to draw upon the powerful learning and reasoning resources that all students bring to the classroom and to create an environment in which the students are active learners. This approach could result in students who develop their capacity to reason about the complex and interesting world and could go a long way toward addressing the rote approach seen in so many contemporary classrooms.

36.2.3 *What Makes a Good Model? Epistemological Concerns*

Given that models are defined only in the context of their use, it follows that there is no context-independent way to evaluate a model. Models are built with an understanding of the epistemological criteria that are relevant to the question at hand, and they are evaluated with an understanding of their intended use. This leads us to consider two epistemological concerns:

1. *A focus on models means merging the contexts of discovery and justification.*
2. *Models must balance trade-offs in epistemological criteria.*

36.2.3.1 Merging the Contexts of Discovery and Justification

Practice-based philosophers acknowledge that there is no meaningful distinction *in practice* between the model development and evaluation. In his 1999 chapter in *Models as Mediators*, Marcel Boumans explores the relationship between model building and model justification. He argues that "models integrate a broader range of ingredients" that include theory and empirical data but also metaphors, analogies, mathematical concepts, and techniques. The central claim of his chapter is that this integration is satisfactory when the resulting model can be (1) used as a solution to a theoretical problem, (2) an explanation of an empirical phenomenon, (3) an indication of some possibilities, and (4) a way to mathematically conceptualize a problem. This is an account of modeling that is situated in the context of function, aims, and cognitive payoffs.

Boumans' central thesis is that despite the way in which stories about model development get told, in practice, the "context of discovery" and the "context of justification" are completely intertwined. It is by simultaneously attending to both the theoretical/empirical world and the more pragmatic aims of the modeler that progress on model development is made and justified. The steps are not distinct. One does not build something and then check to see if it does what it is meant to do. Rather one builds something with ongoing and critical attention to the purposes it is supposed to serve. In this way, Boumans explains that "justification is built-in."

Similarly, Nersessian (1992, 2002), by focusing on the cognitive activities of scientists, combines the contexts of discovery and justification into the context of "development" where ideas are articulated and evaluated in a process that is fundamentally creative. New ideas arise in this context not completely de novo but in conversation with existing ideas. She describes how, for example, Maxwell's revolutionary ideas about electromagnetism were borne out of analogies with existing models in mechanics. Further, in the context of development, emerging ideas are not simply held up against a set of rigid standards of justification, but they can interact with those standards to change the rules of the game. Einstein's new framework of relativity fundamentally shifted the criteria against which models would be judged.

36.2.3.2 Models Must Balance Trade-Offs in Epistemological Criteria

Both the Boumans and Nersessian accounts point to the contingent and contextual nature of scientific reasoning and suggest that models will be subject to different epistemological criteria depending on how one intends to use them. They also suggest, as ecologist Richard Levins argued, that "[t]here is no single, best all-purpose model" (1966, p. 7). Levins argued that for both cognitive and methodological reasons, modelers must often choose among the desirable, but often conflicting, epistemic aims of realism, precision, and generality. For example, a fisheries biologist interested in population projections of a species of interest might choose to sacrifice generality in order to construct a model that can generate accurate predictions of population fluctuations, while an ecologist, like Levins himself, might forgo predictive precision in the interest of general explanatory power. The main point to take away from Levins' argument is that modelers will and should build different models depending on their particular aims. The implication is that there is not a single type of model or modeling that can address all biological problems equally well; depending on the question at hand, a biologist will want to choose the model that is the best tool for the particular job.

36.2.3.3 Implication: The Need to Contextualize Meta-modeling Knowledge

When engaging students in the context of model development (i.e., model construction and evaluation) it is important to make them aware of criteria used to judge models but also to help them develop the expertise to recognize which of these criteria are relevant for their purposes at a specific point. A recent study by Pluta et al. (2011) highlights the importance of helping students develop ideas about what makes models "good" in ways that make the context explicit. Without significant instruction, middle school students were able to generate a variety of epistemic criteria for evaluating scientific models. When prompted to list the features of a "good" model, students responded with criteria such as communication, explanatory power, and fit to data. However, the most common responses had to do with the amount of detailed information presented in the models, suggesting that students were thinking of models primarily as useful for conveying information, much as a textbook diagram would.

Looking closer at the nature of the task in this study, students were asked to evaluate a variety of static representations of models including diagrams, pictures, and text similar to what they might see in textbooks (Pluta et al. 2011, p. 500). The task was framed without reference to a particular problem, question, or aim. Given that in the context of this task students were interacting with static, final form models, it is not surprising that many students described models as tools that help communicate ideas, rather than objects to support scientific inquiry. Nevertheless, this study suggests that students do have some resources for thinking about using models in a variety of ways and it supports the argument that a goal of instruction should be to reinforce and refine these ideas with reference to particular scientific aims. We caution against teaching epistemic criteria to students as a normative list of characteristics of "good models" in an abstract and universal sense but instead advocate for instruction that helps students develop and attend to such criteria in the course of developing and using models in context.

36.2.4 How Are Models Used? Functional Concerns

The primary utility of the practice turn is that it has begun to specify, in more detail, the ways in which models function in scientific practice. Once one takes up the "models *for*" orientation, then a crucial next step is to consider what the cognitive agent is doing in more detail. In what follows we build on what has so far been a general argument that models are context-dependent tools for reasoning and now turn to a more specific account of the ways in which these tools can support sense-making in science.

Here the focus is on three scholars from the science studies literature who have taken up the challenge of elaborating a functional analysis of models in science. Jay Odenbaugh (2005) presents an argument from contemporary philosophy of biology for the legitimacy of modeling in biological practice and the range of uses they are put to in that discipline. Nancy Nersessian approaches the problem from the perspective of cognitive science, using cognitive-historical case studies of physicists and contemporary ethnographic methods to unpack the affordances of model-based reasoning. Stella Vosniadou (2001) considers how models function in scientific sense-making by examining similarities between the reasoning of young children/lay adults and scientists.

36.2.4.1 Odenbaugh: Cognitive Benefits of Modeling in Biology

Philosopher of biology Jay Odenbaugh (2005) presents an argument emphasizing the functional utility of modeling in ecology. He states, “model building is first and foremost a strategy for coping with an extraordinarily complex world” (p. 232). He unpacks the strategies of modeling in ecology and the associated cognitive benefits of engaging in these strategies. While, his analysis draws on work in biology, we find it useful for exploring the role of models in science more generally.[8]

Drawing on the work of Levins (1966), Odenbaugh explores five major pragmatic uses for models in biology and their associated benefits: (1) simple, unrealistic models help scientists explore complex systems, (2), models can be used to explore unknown possibilities (3) models can lead to the development of conceptual frameworks, (4) models can make accurate predictions, and (5) models can generate causal explanations. The focus of his argument is that the first three roles of models have been underemphasized in comparison to the latter two.

In his exploration of the first point, Odenbaugh describes how simplification is a purposeful strategy that scientists use in a number of different ways. For example, Odenbaugh describes how simplistic optimality models, which assume that natural selection is the only mechanism shaping natural systems, are used as a baseline from which to consider and explore deviations. That is, simple models can help scientists by allowing them to begin to unpack the reasons why a false model is wrong (see also Wimsatt 1987).

A simple model can be compared to successively more complex models as a systematic strategy for locating error. Odenbaugh illustrates this point with an account of how understanding the deficiencies in the simplest version of the Lotka-Volterra predator–prey model, which is empirically unrealistic, has led to a productive elaboration of increasingly detailed models. Importantly, these models not only make more sense empirically, they also include assumptions that are much more plausible given what is known about natural populations.

In posing a second role for models, Odenbaugh examines how models afford opportunities for exploring possibilities. Rather than representing what is, models can help scientists think about what might be. For example, Odenbaugh describes how ecologist Robert May explored the possible patterns that would emerge from a simple logistic model of population growth. His analysis revealed that increasing

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[8] See Svoboda and Passmore (2011) for a much more thorough treatment of Odenbaugh’s framework.

the per capita rate of increase (R) could yield chaotic dynamics. The significance of this finding was that it oriented ecologists to the possibility that even relatively simple ecological systems could exhibit complex chaotic patterns for certain parameter values.

The third role for models is in leading to the development of new concepts. Odenbaugh (2005) describes how biologist Robert May chose to represent the overall number and degree of interactions in an ecological community in terms of a "connectance" parameter C, which he defined as the proportion of all pairwise species interactions that were not equal to zero. May's analysis suggested that C played a key role in the stability of the community over time. While May's model was later criticized, Odenbaugh describes how his attempt to operationalize and interpret the role of C opened up a discussion in the ecological community surrounding the appropriate ways to conceptualize community complexity and stability. This analysis marked the beginning of a proliferation of ideas in the ecological community as well as a marked increase in experimental work in community ecology that extended well beyond the original model.

In sum, the essence of Odenbaugh's argument is that matching reality is not the only role for models in biology. Making predictions and explanations are important roles for models, but there are others as well that do just as much to support sense-making. Odenbaugh wants to ensure that the utility of the *exploratory* role of models in generating new ideas and new ways of thinking is recognized as well.

36.2.4.2 Nersessian: Model-Based Reasoning in Physics

Nancy Nersessian and her colleagues have investigated the role of models in science both through cognitive-historical case study analyses (e.g., 1992, 1999, 2002) and more recently in laboratory settings (Osbeck et al. 2010). One of her primary aims has been to explore how models help scientists reason about phenomena by attending to the cognitive processes of scientists and how these processes are situated in scientific practice. In her work Nersessian has identified three types of modeling practices that commonly co-occur in case studies of scientific problem solving: (a) visual reasoning, (b) analogical reasoning, and (c) thought experimentation (simulative reasoning).

In a case analysis of the development of electric-field theory, Nersessian describes the strategies used by Faraday and Maxwell (for a detailed account see Nersessian 1992). Faraday and Maxwell were motivated by a desire to make sense out of a puzzling phenomenon: apparent attractions between objects at a distance. This phenomenon is easily observable by, for example, rubbing a balloon against some fabric and noting that it can now "stick" to the wall. Both scientists made extensive use of diagrams to organize and visualize their emerging understanding of how electric phenomena might work. These representations served to highlight the important structures and relationships between them and served as external objects that could be actively reasoned with. As Nersessian (2002) explains, visual representations do more than hold the ideas in a model—they help focus the reasoner on salient features. They also support simulative reasoning by helping create a visual image that can be animated in the mind. Finally, visual representations provide a way to share ideas with the community. Preparing for this sharing event can force the modeler to make ideas clear and the act of sharing such representations is a productive means of extending the reasoning process out to the larger scientific community. It is the interaction between these externalizations and the underlying model ideas that can lead to breakthroughs for the reasoner.

Analogical reasoning is a form of reasoning that is common in many of these analyses. In forming his understanding of the concept of electricity, Maxwell leveraged analogies from classical Newtonian mechanics. He reasoned that electricity could be analogous to other continuous-action phenomena such as heat, fluid flow, and elasticity (see 1992). For example, using a fluid flow model to map out a similar model of electricity was a crucial part of early work in developing understanding of electric forces.

It is also evident from Nersessian's analysis of his writings that Maxwell relied on simulative thought experimentation to reason through the consequences of his model. This strategy of imagining how a phenomenon might change if certain conditions are changed was also famously used by Galileo. As Nersessian describes:

> According to Aristotelian theory, heavier bodies fall faster than lighter ones. This belief rests on a purely qualitative analysis of the concepts of 'heaviness' and 'lightness'. Galileo argued against this belief and constructed a new, quantifiable representation through sustained analysis using several thought experiments and limiting case analyses…..He calls on us to imagine we drop a heavy body and a light one, made of the same material, at the same time. We could customarily say that the heavy body falls faster and the light body more slowly. Now suppose we tie the two bodies together with a very thin—almost immaterial—string. The combined body should both fall faster and more slowly. It should fall faster because a combined body should be heavier than two separate bodies and should fall more slowly because the slower body should retard the motion of the faster one. Clearly something has gone amiss in our understanding of 'heavier' and'lighter.' (Nersessian 1992, p. 28)

Galileo used this strategy to explore the meaning of the concepts of heavy and light and ultimately reveal the flaws in the Aristotelean model.

Nersessian's focus on model-based reasoning in science draws out some specific cognitive strategies that scientists have at their disposal for making sense of the world. Her analyses make clear that models and the suite of cognitive strategies that they support have helped scientists organize and extend their ideas in ways that have been extremely productive. Further, her account suggests that these same strategies can be productive for students of science (Nersessian 1989, 1995).

36.2.4.3 Vosniadou: Models and Learning Science

Stella Vosniadou has explicitly applied ideas about the cognitive utility of models to science learners. In her 2001 paper, she explores the analogous ways that children and scientists reason with models. Like others, she puts the mental models of children and lay adults on the same dimension as the models of practicing scientists. In her analysis she explores the functions that models play in children's reasoning.

She summarizes her findings with three related functions of models in reasoning: "(a) as aids in the construction of explanations, (b) as mediators in the interpretation and acquisition of new information, and (c) as tools to allow experimentation and theory revision" (p. 359).

In the first sense, Vosniadou notes that models serve a generative function in that they allow the cognitive agent to reason about situations or phenomena that are beyond his or her experience. In her studies of children and lay adults and their views of the shape of the earth, she found that the model served as the "vehicle through which implicit physical knowledge enters the conceptual system" (p. 361). Once this knowledge was articulated in the form of a model, most of her subjects answered questions using a consistent form of this model for the remainder of the study session and were observed to use the abstract ideas to answer specific questions about the earth and objects on it.

Just as the cognitive agent uses the model to generate explanations, so, too, does the model provide a strong filter through which new experiences or information is interpreted. In a study of children's ideas about the day/night cycle, Vosniadou found that the models children had clearly influenced how they interpreted the questions asked of them, just as scientists' models influence how new data are interpreted.

And finally, Vosniadou explores how existing models serve to inform and constrain new ideas and models. In her studies she found that children used their existing ideas to formulate new ones so that a clear connection could be drawn from initial ideas to how those ideas changed over time in the face of new information.

The importance of Vosniadou's contribution is to point out that reasoning with models "is a basic characteristic of the human cognitive system and the use of models by children is the foundation of the more elaborate and intentional use of models by scientists" (p. 367). The fundamental role of models in interpreting and generating new knowledge is central to science and from this premise more specific accounts of the function of models (as delineated above) are possible. Vosniadou's connections between the cognitive work of scientists and children imply that using a modeling framework in education is not only viable but desirable.

From these three scholars, there are a number of ways of describing how models function in science and how this functionality might extend into learning environments. In this final section, we synthesize across these ideas to propose a framework that demonstrates how models, modeling, and model-based reasoning can serve to organize classroom science and focus students' scientific reasoning on making sense of the natural world.

36.3 A Framework for Models in Science Learning

What follows from Sect. 36.2 is that what makes something a model and how a model is developed over time is inextricably linked to the ends it is put to. That is, at a fundamental level, the focus should not be on a model *of* something as an end in itself; rather models are *for* particular sense-making aims. Making sense of a

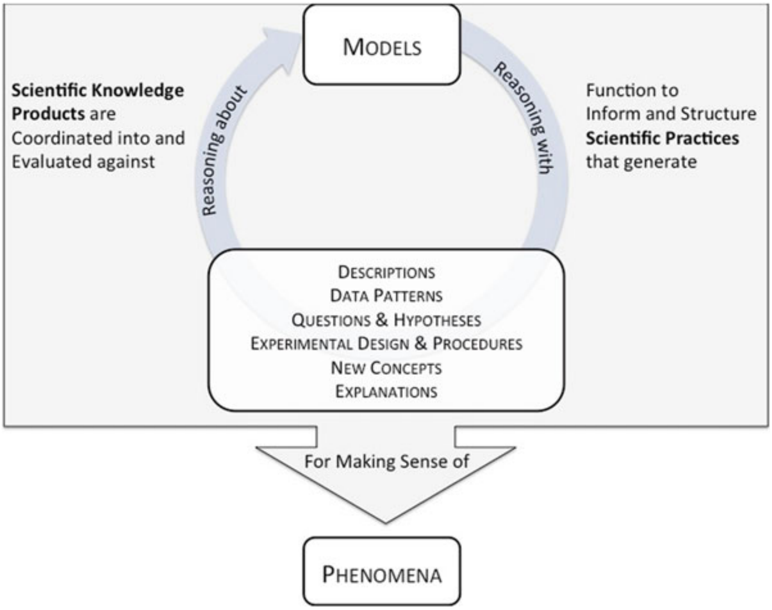

Fig. 36.3 Reasoning with and about models to make sense of phenomena

phenomenon does not typically happen all at once. Rather, one makes sense of a phenomenon by taking the problem in pieces. As these individual pieces come together to inform and constrain the model, both the model and the knowledge products that result from model use become more productive toward the ultimate aim of understanding how something in the world works. Thus, broadly conceived, we delineate two major classes of model-based reasoning. In Fig. 36.3, we have depicted the act of reasoning *with* the model to produce knowledge products and the act of reasoning *about* the model—developing and refining it—using these knowledge products, always toward the ultimate end of sense-making. Thus, the model is a means to an end, not an end in itself.

If models (whether explicit or not) serve as the basis for most, if not all, sense-making endeavors, then getting specific about the myriad ways that model-based reasoning plays out can productively inform science educators as they endeavor to craft more authentic learning experiences for students. Figure 36.3 above is one way to parse reasoning and the products of that reasoning. Of central importance in this figure is the idea that it is through *iterating* between reasoning *with* the model and reasoning *about* the model that one makes progress on coming to understand the phenomenon/phenomena of interest.[9]

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[9] A major caution about the business of categorizing: We do this for the purpose of discussion and because we believe that a consideration of these different cognitive aims is potentially fruitful in the context of education. However, whenever something is presented in a list of categories, a

The challenge with depicting something as an iterative cycle is that it is difficult to know where to begin in discussing it. We do begin with an assumption from cognitive science that in general reasoning is "theory laden" or model based (Vosniadou 2001). Humans are incapable of interacting with ideas or other stimuli without simultaneously doing some level of integrating of those inputs into the cognitive architecture that is already present. In this sense, the cognitive agent does always begin with a model, although it is often implicit.

This does not imply, however, that instruction must always begin with an explicit model. Quite often instruction may begin with a puzzling phenomenon or an interesting data pattern. It may even begin with an explanation or prediction. However, at some point in the instructional sequence, the model must be drawn out in explicit ways so that its full potential as a reasoning tool can be realized.

36.3.1 Reasoning with Models

A major class of reasoning with models is to use them as filters on the world that serve to constrain and bound the problem space. This role of the model is in line with Odenbaugh's exploratory vision of model use (2005). What it is exactly that one finds intriguing about a particular phenomenon is wholly dependent on the model that the phenomenon is examined through. For example, when examining certain physical attributes of an organism, one may be interested in and attend to the genetic basis of a particular trait if the phenomenon is viewed through the lens of genetics models. Alternatively, one might be interested in the selective advantage of that trait in a particular environment if the phenomenon is viewed through the lens of evolutionary models.

An outcome of this kind of reasoning can be a particular description of the phenomenon. In one sense this is a representational task, but prior to any representation, the observer must bound and filter what it is that is worth noticing. This is done with regard to the model and is often the first stage in the sense-making process: defining what it is exactly that is of interest. In educational contexts, this stage is often done for the students prior to instruction in that the articulated learning goals imply a focus on specific models. To return to the example of organism traits, the way in which those traits are defined or described will vary depending on whether the students are supposed to be learning genetics or evolutionary models.

In the process of making sense of what is observed, one typically interacts with the world in particular ways. In figuring out how to manipulate and generate information from the world, one is guided by a current understanding of how the system functions. Interventions are based on models and an explicit attention to them can clarify what it is one wants to know more about and why that information may be

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common interpretation is that that format implies an order. This is not our intention. The point here is that models organize a broad array of cognitive aims beyond representing and explaining which seem to be the two most commonly associated with models (Odenbaugh 2005; Knuuttila 2005).

useful in attaining a higher-order goal of sense-making. Reasoning with a model often points to areas that need further exploration and allows scientists to ask meaningful questions. From these questions, then, a scientist can derive and carry out investigative plans whether those involve data collection or simulations.

Two studies by Metz suggest that the degree to which there is an explicit focus on an underlying model may alter the degree to which students can productively engage in generating meaningful questions and investigations. Metz (2004) reports on a classroom study of elementary school children (second and fifth graders) designed to support the children in articulating and designing their own inquiries. Students had the opportunity to observe crickets and were able to generate many questions about them, but, according to Metz, few of them were scientific (e.g., What different crickets like different foods? What color do crickets seem to prefer? Where would crickets go on the playground?) (Metz 2004, p. 240). Metz does not interpret lack of scientific sophistication of these questions as attributed solely to students' age but rather to a lack of curricular support around question generation. In fact, some students did come up with potentially meaningful scientific questions (e.g., Where do crickets spend their time, in the shade or in the sunlight?) suggesting that students did have some scientifically interesting ideas about crickets but that they may have lacked the support needed to make those questions meaningful, reflecting "the failure of this initial version of the animal behavior curriculum to systematically scaffold theory-building" (Metz 2004, p. 267).

In contrast, Metz (2008) describes a classroom vignette in which students engage in thought experiments to explain the phenomenon that ants walk along the same line to get back to their nest. The focus of this activity was on generating plausible explanations for this phenomenon and then using those tentative explanations to develop a research question that could be tested. Students' tentative explanations were simple models with a relatively small number of constructs and relationships (e.g., ants are detecting some smell in the environment to lead them back to the nest). With these ideas explicitly articulated, the students could focus on attending to how they would collect evidence to support or refute various possibilities. For example, when one set of students devised a broom test that would sweep away the trail, other students could critically evaluate that suggestion in light of the emerging smell model by considering whether or not smell was something that could be removed with a broom. In these two studies, the difference between a focus on sensemaking and question generation in absence of a larger sense-making aim illustrates the potential importance of reasoning *with* a model and in making that explicit in the classroom.

When scientists reason with the model to carry out thought experimentation, they consider "how possibly" something might work. As Odenbaugh points out, this may involve adding particular conceptual elements to the broad framework which then find their way into the model itself. Scientists may then use their current models to develop explanations for how a system might work or to make predictions about the future behavior of that system.

In a study by Berland and Reiser (2011), students use simulation output of an ecological system containing organisms at three trophic levels (fox, rabbit, and grass) to determine the trophic level of a fourth unknown invading organism. In this report on the curriculum, it seems that the model that governed the simulation was largely implicit. This is an example where explicit attention to the underlying ecological models may have altered the student discourse during this activity. The students were engaged in sensemaking, but because the model was not made explicit, an important tool for that sensemaking aim was invisible in the classroom discourse. The primary resource the students had for defending claims was the data representation itself.

Berland and Reiser report on how students were engaged in trying to present arguments in support of their preferred claims. For example, one student countered another student's claim that the invader eats rabbits by explicitly referring to the graph: "you claim that the invader eats rabbits, right? Well, at the end of the graph when the rabbits are dead, how do the invader keep going up?" (Berland and Reiser 2011, p. 202). Underneath the first student's claim that the invader eats rabbits is a model in which the invasive organism shares a trophic level with the fox. Making sense of what this implies could have been supported by first developing a robust understanding of the three organism system and then reasoning through what could possibly happen if an invader was added to the system. This kind of thought experimentation with an explicit focus on the model at work behind the scenes of the simulation may have allowed the students to interpret the invader data more clearly. Such a model would explicitly link population numbers in the fox to the abundance of its food source, rabbit, and would make the prediction that if the rabbit population were to decrease, we would expect a decrease in the fox population as well. Being able to imagine how the system might change in response to changes in variables could help students make theoretically justified claims that they could then hold up against the simulation output.

The operations and outcomes of reasoning with models depicted in Fig. 36.3, collectively, are at the core of sense-making. That is, if a phenomenon is thoroughly described, investigated, and explained, then it has been reduced to some kind of order, or it has been made sense of in the broadest sense. Reasoning *with* a model is core to the scientific practices of observing, describing, asking questions, designing investigations, explaining, and predicting.

36.3.2 Reasoning About Models

Reasoning *about* models refers to the integrated practices of developing, evaluating, and revising models. In Fig. 36.3, reasoning *about* models means making decisions about how to synthesize ideas from a number of different sources in the service of more clearly articulating a model. Boumans (1999) makes the important claim that this work is done iteratively and concurrently with model use and so, again, recalls that these different cognitive strategies are teased apart in the diagram for the purposes of discussion.

Reasoning about a model involves making and justifying a number of decisions. One major class of model-based reasoning involves making representational decisions (Nersessian 2002; Knuuttila 2005). In order to share a model within a community of practice, the model must be externalized in some way. The types of things a scientist attends to in creating these externalizations are often central to the formulation of the model itself. For example, if one chooses to represent a model in mathematical form, there are a range of decisions one must make about how different aspects of the model are laid out and the precise ways that each model idea, as represented in a mathematical expression, relates to others. Then, once a mathematical model is analyzed or a computational model is run, the scientist must interpret the results using the initial framework, checking to see if the model output makes sense and is useful in figuring out something about the system under study.

In an undergraduate context, Svoboda and Passmore describe how the question and the model coevolved over time (2011). Specifically, students in this context were attempting to model vaccination-disease dynamics. The students never had a firm hypothesis that they were attempting to prove or disprove. Rather, the group was engaged in a creative and dynamic process of trying to make sense of a complex phenomenon. Throughout the course of their months-long inquiry, they spent a lot of time reasoning *about* the model with close attention to their initial intentions for modeling the system. They had been inspired to undertake this particular project after reading an article that described how media attention about a possible link between autism and the measles, mumps, and rubella (MMR) vaccine led to reduced vaccination and recent disease outbreaks in countries that have voluntary vaccination strategies.

As they went about their work, they continually returned to their initial goal of making sense of the phenomenon of disease-vaccine dynamics. This attention allowed them to make a series of decisions about what to include in their model, how to represent various aspects of the system, and how to interpret results of their modeling activities.

In the process of crafting a specific articulation of a model and communicating it to others, it is not uncommon to come across aspects of the model that need further expansion. Odenbaugh (2005) delineates this as a process of conceptual development. Deciding on, describing, and defining the working pieces of the model are all involved at this point.

Another class of reasoning *about* the model comes when one considers the relationship between particular phenomena and models. Often, a model is developed in the context of examining a very specific phenomenon. For example, one might model the relationships between a set of organisms in a particular environment. Doing so, by necessity, involves attending to the specific details of those organisms in that environment. The model may be deemed useful for explaining one very specialized situation, but from there one might wonder if the model could be applied to other similar phenomena. So, another way in which reasoning about the model occurs is to consider the generalizability of a particular model. One aspect of this may be to make representational decisions about how to broaden the model focus beyond a particular phenomenon to make it useful to explain a larger class.

To come back to the intertwined issues of "discovery and justification" (Boumans 1999), it is in the process of thinking explicitly *about* the model that model development and evaluation come together. Iterating between model use and meta-level processing about the extent to which the model is achieving one's aims is at the core of evaluating a model. The scientist reasons with a model to develop explanations and/or predictions and from there considers whether those knowledge products are useful or not. If not, it may be necessary to consider if the issue is related to the model itself, thus suggesting a need for revision, or if it is an issue of translating the model into an explanation that is at play.

In all cases, issues around reasoning about the model must be inextricably tied to the intention of the modeler. There is no context-free way to make reasonable decisions about the attributes and form of a model. These decisions, in practice, must always be made with regard to the purpose the model is put to in the context of its use.

A study by Hmelo-Silver and Pfeffer illustrates this point. They describe how students had trouble constructing models of aquaria that extended beyond superficial structural features, while experts tended to include deeper functional relationships (Hmelo-Silver and Pfeffer 2004). One way to understand this difference is to ask how each of these groups interpreted the purpose of this model development task. It is clear that experts brought a particular set of aims and purposes to the task. For example, expert aquarium hobbyists were concerned with the aim of maintaining healthy fish and tended to include variables and the relationships among variables in aquaria that are related to fish health. In contrast, ecologists constructed models that could be used to explain ecosystem stability over time.

That students attended to surface features suggests that they viewed the task as primarily descriptive (i.e., they were supposed to be building models *of* aquaria). Rather than propose that students are not as good as experts at attending to deeper features, this as an example where the students needed additional scaffolding around the purpose of model development.

While this work is important because it gave students the opportunity to take responsibility for model development, without an explicit aim, students had no way to productively bound what they were modeling or make decisions about what to include and what to leave out. If instructors do not make the purpose of a modeling activity clear to students, they will bring their own frame to it, and that framing, without explicit attention, may be idiosyncratic rather than shared across the group. If model development and justification cannot be decoupled, then there is simply no robust way to engage in model development in the classroom in the absence of a clear aim that can guide the evaluation/justification of the model.

In contrast, Smith and colleagues (1997) describe how groups of ecology students constructed models relevant to an aphid-wasp-fungus system. Crucially, prior to constructing models, the students were first asked to develop questions that they were interested in investigating. The students were then able to make decisions about the degree of detail and complexity to add into their models. Different groups of students, depending on the question they proposed and the aims they prioritized, then constructed very different models.

A growing number of scholars have written about the importance and utility of allowing students to construct and critique models.[10] What the science studies lens brings to such environments is the importance of coupling model development and evaluation to a clear sense-making aim. In order for students to make the appropriate decisions about how to bound and describe a system, they need to have a clear sense of what the model will ultimately used to do.

What these examples are meant to draw out is how, when contextualized in this way, the practices of constructing, representing, evaluating, and revising models can support productive sensemaking work. These examples highlight how reasoning about models is inextricably linked to considerations of what those models can then be used to do. Thus, reasoning *about* the model is done with critical attention to the output of reasoning *with* the model to achieve a particular aim. When these practices are not linked in instructional settings, then the outcome may not realize the full potential of model-based reasoning in supporting learning.

36.4 Major Implications and Recommendations

36.4.1 Implications

To consider a view of the various aims that a modeler can have and pay explicit attention to the two major classes of model-based reasoning identified above has implications for the way in which science educators approach science instruction and the degree of student ownership and autonomy. Moreover, a focus on models provides a framework in which the various practices of science can be organized and put to productive use in the classroom.

Much has been made over the past few decades about teaching for conceptual change. As part of this approach, many science educators have been involved in determining a canon of scientific ideas. What if the criteria for what counts as the canon were shifted? Obviously scientists do not undertake their cutting-edge work aiming at an established canon of models. To present the task in science classrooms as one in which the students are trying to uncover or guess the canonical model seems disingenuous at best. Maybe there is, however, a canon of classes of phenomena that a scientifically literate student should be able to explain, and those explanations are based on a developmentally appropriate set of models. In this way instruction could actually be crafted authentically, and the intellectual environment of the classroom could reflect the particular sensemaking aims of the community of learners at any given time while concurrently fostering deep understanding of important science concepts.

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[10] See, for example, Baek et al. (2011), Clement (1989, 2000), Gilbert et al. (1998a, b), Hogan and Thomas (2001), Passmore and Stewart (2002), Schwarz et al. (2009), Svoboda and Passmore (2011), and White (1993).

As students engage in the kind of reasoning described here, they should develop a greater sense of ownership over ideas as they develop them iteratively to address specific reasoning aims that their classroom community has identified. Many of the studies cited above bear witness to the fact that students will engage in complex reasoning when tasks are designed that require it. By organizing these tasks in explicit ways with regard to reasoning with and about models, students may develop a sense of autonomy and begin to demand learning environments that are fundamentally about figuring things out about how the world works.

The framework presented here unites and organizes a number of practices that science educators have been focused on for the past several years (NRC 2007, 2011). The centrality of models to the practices of asking questions, designing investigations, developing explanations, and arguing from evidence becomes clear for both students and teachers. Sadly, higher-level goals of science do not seem to drive science education which tends to focus on the practices in ways that are potentially isolated from higher-order sensemaking goals of explanation (Metz 2006). Placing a model-based view of science at the center of the practices has the potential to counter the treatment of each practice as isolated and unite them in service of sense-making.

36.4.2 Research Recommendations

From the view of models in science presented here, there are a number of research avenues for investigating how models operate in learning science. In Sect. 36.3 we explored the real or imagined role of an explicit focus on models in learning environments that have been described in the science education literature. However, more detailed work is needed in this area to understand exactly how a focus on models and modeling interacts with learning both the conceptual content of particular scientific disciplines and how it may influence students' epistemological views. A recent article by Eve Manz (2012) is one example of this type of scholarship.

If the field can agree on a set of guiding principles for what modeling entails in science learning, then a series of deep investigations into learning environments will be possible that simultaneously attend to the particulars of each context and provide insights into a broader framework. As it stands now, there is a wide range of conceptualizations around modeling and its relationship to other scientific practices, and thus, it is sometimes difficult to understand how different studies speak to one another.

Further, there will need to be additional research on teacher conceptualizations and enactments around model-based inquiry. This work is underway,[11] but it is clear that teachers (both preservice and in-service) have had very little experience with a view of science as a model-based enterprise and thus may be challenged to enact

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[11] See, for example, Danusso et al. (2010), Nelson and Davis (2012), and Schwarz and Gwekwerere (2006).

model-based curricula (Windschitl et al. 2008a). As researchers uncover and delineate some of the challenges teachers face in supporting students in model-based inquiry, additional resources can be developed to support teachers, including comprehensive curriculum.

36.5 Conclusion

This chapter was crafted to answer questions about the function of models in science and how that view could be translated for educators. The practice turn in science studies has been fruitful in focusing the scholarly community on the importance of models and in identifying the particular ways in which models function in the intellectual lives of scientists. The science studies' work has informed science educators and the time has come to more fully incorporate the findings from philosophical, historical, and cognitive studies of science into science education.

So, in the end we are hoping to make what may seem a subtle shift but one we find incredibly important and powerful in thinking about science education. Instead of listing the kinds of models there are and arguing about what the canonical set of target models for instruction might include, we suggest that the dialogue becomes one that is centrally about the context-dependent roles that models are playing in the students' reasoning/sense-making about phenomena. In making instructional and curricular decisions based on a "models *for*" orientation, we expect a more productive and hopefully authentic version of school science to emerge.

If it is relatively uncontested that models form the basis of most reasoning in science, then it seems obvious that they should form the basis of reasoning in science classrooms. And, although this is often the case when we examine productive classroom activity, the models are rarely made explicit. There may be much to be gained from changing this state of affairs, but ultimately that is an empirical question. The presence of and attention to models as used by cognitive agents *for* specific purposes both focuses and organizes the cognitive activity that is primarily aimed at sense-making. As science educators take seriously the "practice turn" and call for authenticity, it will be a central focus not only on models but also on what they are being used *for* in the sense-making process that will provide a way forward.

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Chapter 37
Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implications

Zoubeida R. Dagher and Sibel Erduran

37.1 Introduction

The teaching of history and philosophy of science (HPS) in science education has been advocated for several decades.[1] In recent years, however, there has been increasing interest in the philosophical examination of biology and chemistry as distinct branches of science that differ epistemically from physics in significant ways. Philosophers of biology (Hull 1973; Mayr 2004; Ruse 1988) and philosophers of chemistry (Bhushan and Rosenfeld 2000; van Brakel 2000; Scerri and McIntyre 1997) have offered insights into the epistemologies of biology and chemistry. However, these insights have not been integrated sufficiently into biology and chemistry education research, curriculum materials and classroom practice. Research on the nature of science in science education could benefit from such insights in order to improve understanding of not only the disciplinary knowledge but also the meta-level characterisations of scientific knowledge at large.

As science educators we are concerned with the question of how philosophical insights into scientific knowledge can inform science teaching and learning. The goal is not to contribute to the debates in the philosophy of biology and chemistry,

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[1] See for example Duschl (1990), Hodson (1988), Matthews (1994/2014) and Schwab (1958, 1978).

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but rather to draw out some aspects of these debates that are relevant for education in light of evidence from empirical studies in science education (e.g. Dagher and Cossman 1992; Erduran and Jimenez-Aleixandre 2008; Sandoval and Millwood 2005). In doing so, we problematise the current state of under utilisation of the epistemological aspects of disciplinary knowledge in science education and illustrate with examples how it can be practically addressed. It is hoped that the discussion will assist other science education researchers in exploring the philosophical literature for clarifying and justifying educational goals that relate to scientific knowledge claims.

According to Irzik and Nola (Chap. 30), science can be perceived as a cognitive-epistemic system and as a social system. Scientific knowledge, which constitutes one component of the cognitive-epistemic system, is the culmination of scientific inquiry and includes laws, theories and models. Focusing on these structural elements in the context of any single discipline would be necessary to understand the nature of that discipline. Among these elements, explanations and particularly laws have been understudied from an epistemological perspective in science education research. For instance, while there is a substantial body of literature focused on models (e.g. Justi 2000), the study of the particular epistemological aspects of models has been scarce (e.g. Adúriz-Bravo 2013; Adúriz-Bravo and Galagovsky 2001; Erduran and Duschl 2004). Similarly, despite the importance of laws and explanations in the science disciplines, relevance of their epistemic nature to educational practice is seldom explored (e.g. McComas 2003; Sandoval and Reiser 2004).

One often-cited misunderstanding of the nature of science (NOS) concerns scientific laws. Classified as the number one NOS myth by McComas (1998), many individuals tend to believe 'that with increased evidence there is a developmental sequence through which scientific ideas pass on their way to final acceptance as mature laws' (p. 54). Involved in this belief is the thought that science starts out with facts, progresses to hypotheses, then theories, then, when confirmed, to laws. Another myth pertains to the idea that scientific laws are absolute (McComas 1998). These beliefs represent only two of many other misunderstandings about the nature of scientific knowledge and pose challenges regarding the best approach to deconstruct them. Several approaches have been proposed for countering these and other nature of science misconceptions (Clough 1994; Khishfe and Abd-El-Khalick 2002; Schwartz et al. 2004), but it remains unclear whether efforts to enhance student understandings of the nature of science have resulted in significant or lasting improvements (Lederman 2007).

The context of laws provides a crucial and relevant nexus for promoting the epistemological aspects of biology and chemistry in the classroom. Focusing on the nature of laws in biology education, for example, not only serves to clear existing misconceptions (as the ones mentioned earlier) but offers insight into basic metaphysical and ontological aspects of the discipline which can enhance student understanding of the subject. The inclusion of 'laws' in chemistry education not only elaborates on this important philosophical thesis but also offers some insight into how students' interest in philosophical aspects of chemistry might be stimulated.

Scientific explanations on the other hand refer often to how and why something happens (Chinn and Brown 2000). Typically scientists explain phenomena by determining how and why they occur along with the conditions surrounding the observed events (Nagel 1961). Explanations are important components of scientific theories. They are the backbone of scientific claims and are consequently a central target for epistemological disputes. It is through the refutation or support of components of scientific explanations that the fabric of theories is woven. In science education, considerable emphasis is placed on developing students' ability to substantiate their explanations using reasons and evidence.

Despite the separation of laws and explanations for contrast in biology and chemistry in this chapter for educational purposes, the distinction of these concepts in the history of philosophy of science is not straightforward. For example, the covering laws in Hempel's positivistic framework function not only as core explanatory components (*explanans*) but also as the targets of explanation (*explananda*). In more recent work, lawlike regularities among properties are considered to be a kind of explanation in their own right. For instance, Bird (1998) calls them 'nomic explanations'. He argues that inferring a law from observation is a form of *inference to the best explanation* (IBE), a common form of scientific reasoning.

The task in this paper is not to articulate the distinctions between laws and explanations from a philosophical perspective. Indeed, as educators, it is beyond the scope of our engagement in philosophy of science to contribute to or resolve existing debates or to generate new knowledge in the field. This task is left to the professional philosophers. Rather, the purpose of this analysis is to draw out some themes around laws and explanations, discussed in philosophy of biology and philosophy of chemistry, in ways that are relevant for science education. For example, Mendel's Laws and the Periodic Law are chosen as examples because of their prominence in science curricula at the secondary school level, which is our primary area of interest. At times, the discussion will refer to some contentious characterisations of laws and explanations. Again, here the discussion is reflecting ongoing debates to inform the science education community of the sorts of issues that are of concern to philosophers of science. The implications for science education could include problematising the nature of laws, explanations or indeed the contrast itself. However, given the typically separate reference to laws and explanations in the science curricula, the goal in this chapter is to interrogate the existing literatures for particular and explicit references to either laws or explanations thus informing subsequent analysis of how they are depicted in science education.

Furthermore, while discussions of NOS in the science education literature typically focus on the relationship between laws and theories (specifically on how they are different), they tend to neglect the conceptual disciplinary-based features that pertain to them. Shifting the discussion in this paper from laws and theories to laws and explanations underscores the following key ideas/assumptions: (1) Explanation is a key purpose of science. Theories are developed not as ends in themselves but as powerful explanatory and predictive tools. (2) Laws express regularities that can serve predictive and/or explanatory functions. (3) Explanations are building blocks of scientific theories that can be explored pedagogically at multiple organisational levels. (4) explanations are pragmatic and contextual (de Regt 2011).

Focusing on explanations rather than theories in this paper allows for a nuanced and contextual discussion of their characteristics across disciplines and subdisciplines from philosophical and educational perspectives. The significance of explanations in science curriculum and instruction is recognised by science educators in a variety of ways. In some cases, concern is expressed about linguistic and epistemic aspects, as with Horwood's (1988) illustration of the lack of consistency between the terms 'explain' and 'describe' in teaching materials and Jungwirth's (1979) findings that high school students tend to equate anthropomorphic and teleological explanations with causal explanations. At the level of instruction, teachers are reported to use a wide range of explanatory types some of which are scientific and some are not, calling for further examination of the appropriateness of these explanations (Dagher and Cossman 1992). More recent work presents evidence for the difficulties experienced by students in generating and justifying scientific explanations (Sandoval and Millwood 2005). In addition, there have been ongoing efforts focused on designing instructional models for supporting student development of scientific explanations (Land and Zembal-Saul 2003; McNeill et al. 2006; McNeill and Krajcik 2012).

In summary, the purpose of this chapter is to discuss characterisations of laws and explanations in biology and chemistry and extract some implications for teaching, learning and curriculum. The goal is to demonstrate how some of the ongoing debates about the nature of laws and explanations in biology and chemistry can have useful contributions to teaching these disciplines without necessarily resolving these debates. Exploring the arguments in these debates allows the articulation of how laws and explanations as products of scientific knowledge might be addressed more meaningfully in educational settings by discussing current coverage of laws and explanations in typical biology and chemistry textbooks. The chapter concludes with recommendations for revising textbooks and instruction in ways that restore the grounding of subject matter knowledge in its epistemological context.

37.2 The Nature of Laws and Explanations in Science

Volumes have been written about the nature of laws and explanations in science, mostly using physics as a basis for analysis. Views about the purpose and nature of these entities have changed over time and some aspects of them continue to undergo some debate. Attempting to summarise this vast literature or represent the diversity of views in few paragraphs is impossible without doing grave injustice to the field. It is necessary, however, to highlight key ideas before discussing the characteristics of laws and explanations in biology and chemistry with the understanding that this brief overview is not exhaustive or representative of extant viewpoints.

What distinguishes a law of nature from any other regularity? Traditional definitions of a scientific law typically refer to 'a true, absolute and unchanging relationship among interacting elements' (Dhar and Giuliani 2010, p. 7). This traditional view has been challenged on several bases. Lange (2005) argues that the condition of truth alone does not help make this distinction since other regularities are true also. He proposes the following four criteria to aid in distinguishing laws of nature from other regularities: necessity, counterfactuals, explanatory power and inductive confirmations. Mahner and Bunge (1997) have argued that laws are said to be 'spatially and temporally boundless', where other laws may be 'bounded in space and time'. Cartwright's critique of 'the limited scope of applicability of physical laws' (Ruphy 2003) problematises the 'truth' aspect of laws. Giere (1999) on the other hand holds the view that what has come to be known as 'laws of nature' is in fact historical fossils, holdovers from conceptualisations first proposed in the Enlightenment. He proposes the consideration of models, which he argues are more reflective of how science is actually *practised*.

The significance of the debates about the nature of scientific laws becomes most relevant when discussing the role they play in supporting explanations in the specific sciences. Attempting a balanced description of scientific laws is a complex undertaking considering debates among philosophers about criteria invoked to distinguish between various types of laws such as strict versus *ceteris paribus* laws and empirical versus a priori laws. Such criteria include mathematical models, necessity, and explanatory and predictive potential. Some of these debates will be revisited in the context of the specific sciences later in this chapter.

In an insightful paper written more than five decades ago, Bunge (1961) classified lawlike statements from various philosophical standpoints into more than seven-dozen kinds. He concluded his detailed analysis with calling for less stringent philosophical restrictions regarding what could be classified as a law:

> There are as many classifications of law statements as viewpoints can be profitably adopted in their regard, and there seems to be no reason—save certain philosophical traditions—why most law statements should be regarded as nonlaw statements merely because they fail to comply with either certainty, or strict universality, or causality, or simplicity, or any other requisite found necessary in the past, where science seemed to concern itself exclusively…. That lawlike (*a posteriori* and general in some respect) statements be required corroboration and systematicity in order to be ranked as law statements, seems to fit contemporary usage in the sciences. (Bunge 1961, p. 281)

Bunge's pragmatic view regarding what constitutes scientific laws is a profound one. Continued debates about what counts as a scientific law, argued with core propositions of particular science disciplines, seem to be fundamentally grounded in normative or pragmatic standpoints and from this perspective cannot be said to have been fully resolved. Perhaps the most valuable context for such debates has been relative to the role of laws in generating or supporting scientific explanations (Press 2009).

Explanation is often hailed as one of the main goals of the scientific enterprise. Nagel (1961) articulates the central role of explanations in science when he states: 'It is the desire for explanations which are at once systematic and controllable by factual evidence that generates science; and it is the classification and organisation of knowledge on the basis of explanatory principles that is the distinctive goal of the sciences' (p. 4). While this stance towards explanation may seem obvious, it does not represent a united or a longstanding view. Logical positivists for instance, led by Ernest Mach, held that the aim of science is not to explain but rather to describe and predict phenomena (de Regt 2011). Discussions of the components that distinguish scientific explanation from other forms of explanation have spurred significant philosophical debate and led to a variety of accounts that have expanded understanding of their diversity.

The following discussion focuses on describing three main families or models of explanation. These are nomological explanation, causal explanation and functional explanation. According to de Regt (2011), these models are not mutually exclusive but can be used to explain the same phenomenon or explain phenomena in different disciplines.

The deductive-nomological (D-N) or covering law model of explanation proposed by Hempel and Oppenheim (1948) frames explanation as a logical argument in which the conclusion, or *explanandum,* follows from a set of premises, or *explanans.* The premises that constitute the *explanans* have to include at least one general law and other relevant preconditions. The general law in Hempel's account is a key component of the explanation process and has to be a 'true universal generalisation', allowing for the explanation and/or prediction of various events. One of the unresolved issues in the D-N model of explanation, pointed out by de Regt (2011), is that science is usually concerned with the explanation of laws, which necessitates the use of other more general laws. This proves to be problematic without 'giving an adequate criterion for the generality of laws' (p. 159). One derivative of nomological explanation is the inductive-statistical explanation (I-S), in which the law used in the *explanans* contains high probability that subsequently gives rise to an inductive (as opposed to deductive) support to the *explanandum.*

The Causal Mechanical (CM) model of explanation moves away from the conception of explanation as an argument (Salmon 1984). In generating this model, Salmon abandoned the attempt to characterise explanation or causal relationships in purely statistical terms. The CM model employs several central ideas. A causal process is a physical process, like the movement of a ball through space, that is characterised by the ability to transmit a mark in a continuous way. A mark is some local modification to the structure of a process. A process is capable of transmitting a mark if, once the mark is introduced at one spatiotemporal location, it will persist to other spatiotemporal locations even in the absence of any further interaction.

Causal processes contrast with pseudo-processes that lack the ability to transmit marks. An example is the shadow of a moving physical object. The other major element in Salmon's model is the notion of a *causal interaction.* A casual interaction involves a spatiotemporal intersection between two causal processes which modifies the structure of both—each process comes to have features it would not have had in the absence of the interaction. A collision between two cars that dents both is a paradigmatic causal interaction. According to the CM model, an explanation of some event *E* will trace the causal processes and interactions leading up to *E* (Salmon calls this the *etiological* aspect of the explanation), or at least some portion of these, as well as describing the processes and interactions that make up the event itself (the *constitutive* aspect of explanation). In this way, the explanation shows how *E* ‘fit[s] into a causal nexus’ (Salmon 1984, p. 9).

Functional explanations typically account ‘for the role or presence of a component item by citing its function in the system’ (de Regt 2011, p. 164). This type of explanation is commonly employed in the life and social sciences because these domains typically deal with ‘complex organized systems, the components of which contribute to the working of the system (organisms, human minds, societies and so forth)’ (de Regt 2011, p. 164). Achinstein (1983) presents three categories of functional explanations: the good-consequence doctrine in which the function confers some good on something or someone; the goal doctrine in which the function contributes to a goal that something, its designer or its user has; and the explanation doctrine in which the function includes causes or reasons or consequences. These categories probably make it easier to differentiate between functional explanations with teleological goal-oriented tendencies (the second doctrine) and other functional explanations. Achinstein further distinguishes between three types of functions: design functions, use functions, and service functions, allowing for a more nuanced and contextual differentiation between different functional explanations.

Philosophers of science have discussed a plethora of explanation models.[2] Additional contributions have came from philosophers of biology (e.g. Rosenberg and McShea 2008; Schaffner 1993; Sober 2008) and philosophers of chemistry (e.g. Goodwin 2008; Scerri and McIntyre 1997; van Brakel 2000) presenting and defending explanatory models that communicate the uniqueness of their disciplines. The following section describes the characteristics of laws and explanations in biology and chemistry focusing on aspects that have direct implications for science education.

37.3 The Nature of Laws and Explanations in Biology and Chemistry

37.3.1 Laws in Biology

There has been considerable discussion among philosophers regarding the appropriateness or meaningfulness of the concept of law in biology. Mayr takes the stance that ‘laws play a rather small role in theory construction in biology’. He attributes this ‘to the greater role played in biological systems by chance and randomness. Other reasons for the small role of laws in biology are the uniqueness of a high percentage of phenomena in living systems as well as the historical nature of events’ (Mayr 2004, p. 28). The fact that biological systems are governed by ‘dual causation’ imposed by natural laws and by ‘genetic programmes’ makes the

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[2] For example, see Giere (1988), Harré (1988), Hesse (1970), Pitt (1988), Salmon (1987), and Scriven (1970).

theories that explain them distinct from those pertaining to physical systems (Mayr 2004, p. 30). For Mayr, the matter is not one of nomenclature but one of substance. He concedes that even though some of the important concepts in biology ‘can be phrased as laws, they are something entirely different from the Newtonian natural laws’ (Mayr 2004, p. 30).

Garvey (2007) takes a position similar to Mayr’s when he states that ‘Biology does not have strict mathematical laws of its own. There are, as in any science, generalisations. But these generalisations have a habit of proving to be: (i) not distinctive to biology; (ii) not strict, exceptionless, mathematical laws; or (iii) not laws at all. Put in more positive terms, the generalisations found in biology are: (i) laws that belong to other sciences, (ii) *ceteris paribus* laws[3]; or (iii) true by definition’ (p. 157–158). Others such as Uzman (2006) maintain that some biological observations tend to be presented as theories at a time when they should be considered laws of nature. He identifies four laws:

First law: “All phenomena of life are consistent with the laws of chemistry and physics.”
Second law: “The cell is the fundamental unit of life.”
Third law: “Life is continuous across generations.”
Fourth law: “Life evolves – populations of organisms change genetically and irreversibly through time.”

Örstan (2007) attributes to E. O. Wilson the claim that biology has 2 main fundamental laws: ‘1. All of the phenomena of biology are ultimately obedient to the laws of physics and chemistry, and 2. All of the phenomena of biology have arisen by evolution thru[sic] natural selection’. It can be argued, using Garvey’s criteria, that even these ‘laws’ constitute generalisations that are nonmathematical and/or true by definition.

Reasons advanced in support or opposition to the concept of laws in biology can be found in various subdisciplines (evolutionary biology, systems biology, molecular biology, ecology). While the complexity of biological systems is widely acknowledged, constant efforts are being undertaken to establish fundamental biological organising principles that exhibit lawlikeness. For example, Dhar and Guiliani (2010) present an approach for uncovering fundamental organising principles in systems biology. Dodds (2009) has identified 36 laws in ecology to minimise the perceived complexity in interpreting ecological systems. McShea and Brandon (2010) recently proposed a detailed account for a ‘Zero Force’ evolutionary law that they believe to be to biology what Newton’s first law is to physics. These efforts demonstrate that the complexity and contingencies inherent in biological systems have not discouraged biologists and philosophers of biology from trying different approaches to generating ‘fundamental organising principles’.

To attain the ideal status of a universal law, Dhar and Guiliani (2010) believe that what biologists need to do but is difficult to attain is to construct generalisations

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[3] The Latin *ceteris paribus* stands for ‘all things being equal’: *ceteris paribus* laws are laws that have exceptions, often contrasted with strict or ‘real’ laws (Garvey 2007).

that connect all levels from atoms to ecosystems. From their perspective, Mendel's Laws provide a reasonable framework at the phenotypic level, but an equivalent framework is absent at the cell-cell level. They believe, however, that just because this framework is currently absent does not mean it is not attainable in principle. Thus, there is optimism about the possibility of identifying powerful generalisations at the different levels of organisation (Dhar and Giuliani 2010) or developing empirical biological laws (Elgin 2006). In Elgin's (2006) view, a 'distinctively biological law' is one in which 'two conditions must be met: (1) all non-biological concepts in it must be mathematical, (2) It must contain at least some biological concepts and these concepts must be essential to its truth' (Elgin 2006, p. 130).

Other philosophers of biology take a pragmatic approach that 'replaces a definitional norm with an account of the *use* of scientific laws' (Mitchell 2000, p. 259). From Mitchell's perspective, 'the requirements for lawfulness fail to reflect the reality of scientific practice. As a consequence, the traditional understanding of laws is incomplete and fails to account for how humans have knowledge of the complexity of the world' (Mitchell 2009, p. 53). Mitchell characterises the reasons used to deny the existence of laws in biology as rooted in a normative orientation that regard laws along the Popperian tradition: 'bold, universal, exceptionless' (Mitchell 1997, p. S473). Arguing against the privileging of a very special type of generalisation that meets very stringent conditions and occurs very rarely even in physics, she affirms that 'the contingency of generalizations in biology or other sciences does not preclude their functioning as 'laws' – generalizations that ground and inform expectations in a variety of contexts' (Mitchell 1997, p. S478).

Mendel's Laws of segregation and independent assortment are popular topics for debating the nature of biological laws. Briefly stated,

> Mendel's first law, the Law of Segregation, states that while an organism may contain a pair of contrasting alleles, e.g. Tt, these will segregate (separate) during the formation of gametes, so that only one will be present in a single gamete, i.e. T or t (but not both or neither). Mendel's second law, the Law of Independent Assortment, states that the segregation of alleles for one character is completely random with respect to the segregation of alleles for other characters. (Dictionary of Botany 2003)

However, neither their highly contingent nature (Mitchell 2009) nor the historical ambiguity surrounding their ascendance from principles to laws (see Footnote 2 and Marks 2008) is adequate for demoting them to accidental generalisations. Rather than deny the existence of biological laws, it is more useful in the context of the variation inherent in biological systems to provide "a better understanding of contingency so that we can state the many ways in which laws are not always 'universal and exceptionless" (Mitchell 2009, p. 63).

37.3.1.1 The Case of Mendel's Laws in Biology Textbooks

Mendel's Laws of segregation and independent assortment are often described in biology textbooks to various levels of detail with some reference to Mendel's profile and pea-plant experiments. Inheritance is a classic topic in middle and high school biology curriculum materials. A typical chapter in one high school biology book (BSCS 2003) begins with getting students to consider similarities of features between members of different generations in families. Starting with discussions about familiar experiences, the chapter invites students to read the tragic case of haemophilia in the family of the last Czars then leads them to work on different scenarios in order to predict inheritance patterns. Next, students are engaged in simulations, using beans, to help them understand the inheritance of one and two traits. The chapter explores inherited patterns, defines gametes, describes meiosis, tracks genes and chromosomes through meiosis by guiding students to construct a physical representation that tracks the genotype of the newly divided 'cells' and addresses the role of sample size in leading to more accurate predictions. Next the book introduces Gregor Mendel and a video segment that provides data for students to use to make predictions then compare their predictions with actual results provided by the teacher. Additional exercises pertaining to linked and sex-linked traits are offered to deepen and elaborate the concepts before the chapter ends with a discussion of the genetic basis for human variation.

Of particular interest to this paper is the text book's reference to Mendel's second law. The following excerpt represents one of two occasions in which it is mentioned in one chapter: 'When you follow the inheritance of 2 traits (a di-hybrid cross), more complex patterns result. In garden peas, the genes for the traits of pod color and pod shape are on different chromosomes. As a result, their inheritance conforms to Mendel's Law of independent assortment' (BSCS 2003, p. 438). The only other significant reference to this law appears later in the book in an essay at the end of the unit. The essay discusses the concepts of phenotype and genotype and concludes with an example that demonstrates the random inheritance of traits demonstrating how a baby rabbit may inherit different genes for particular traits from the father and mother like fur colour and eye colour independently of each other. The essay concludes with the following historical narrative:

> The principle of independent assortment was discovered more than 150 years ago in a small European monastery garden. A scholarly monk named Gregor Mendel used pea plants to study patterns of inheritance. Mendel experimented with many generations of pea plants. His insights later became the cornerstone for explaining basic patterns of inheritance. (BSCS 2003, p. 499)

As seen in these excerpts, the same concept is referred to as a law in one section of the book and as principle in another. It is not clear whether the shift in language is accidental or whether it refers to the historical evolution of this idea from 'principle' at the time of its inception to 'law' in later references to this idea.[4] While inconsistency in how textbook authors use categorisations of scientific knowledge has been already

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[4] In his review of early textbooks, Marks (2008) notes that, initially, Mendel's Law was often presented in the singular in contrast to Galton's Law of Ancestral Heredity as evident in Punnett's 1905 textbook and most other genetics textbooks of the first generation. In his 1909 book, Bateson contrasted Galton's Law against the Mendelian ''scheme', 'principles', 'phenomena', 'methods', 'analysis', 'facts''. (Marks 2008, p. 250). First references to Mendel's Law of Segregation and Law of Independent Assortment appeared in Morgan's second book in 1916 and were further detailed in his 1919 book *The Physical Basis of Heredity*.

documented (e.g. McComas 2003), noting this inconsistency in this paper underscores what appears to be confusion or lack of clarity about the purpose that this law/principle serves, as demonstrated in both excerpts. The textbook provides no further details about what the 'law' or 'principle' of independent assortment entails or the role it plays in explaining phenomena. It is stated casually as a claim that explains some observations, no different than another claim in terms of its generalisability (or lack thereof) or ability to explain or predict. It is not made explicitly clear that this generalisation can be used to explain or predict phenotypes and genotypes of new generations of siblings that go beyond the specifics of the examples discussed in the chapter.

The main issues in the examples quoted earlier are (1) the striking lack of clarification about what a law entails, (2) the unexplained switch from 'law' in the chapter to 'principle' in the historical anecdote and (3) lack of explicit reference to the relative strong explanatory power (Woodward 2001) expressed that is qualitatively and quantitatively different from other concepts presented in the textbook.

In another high school biology book (SEPUP 2011), the discussion of Mendel's work is devoid of references to laws or principles. Some 60 pages after describing the historical work of Mendel, and only in the context of discussing genes and chromosomes, there is a brief reference to one of Mendel's Laws:

> When the chromosomes line up before division, the paternal and maternal chromosomes in the pair line up randomly and separate independently of each other. This is called independent segregation of the chromosomes. Independent segregation of chromosomes explains the behavior of genes that follow Mendel's law of independent assortment. It also accounts for the fact that genes that are linked on the same chromosome don't follow the law of independent assortment…. (SEPUP 2011, p. 356)

This passage illustrates how Mendel's Law of independent assortment exerts an explanatory function. But it is the only place other than the 'Glossary' section at the end of the book where this law is identified. The apparent retreat from explicit emphasis on Mendel's Laws in both textbooks either reflects a general trend of accidental nature or an outcome of authors' awareness of the philosophical controversy about laws in biology. In both cases, avoidance of explication of the significance of laws or principles in biology in the context of a specific content, such as the one explored here, reduces the likelihood that students will understand the usefulness of this aspect of scientific knowledge relative to its explanatory function. One way to rectify this matter is by using language consistently in textbooks, clarifying what the referents mean and educating readers about the distinctive nature of laws in biology, noting their relevance to explaining observations and predicting new ones. Alternatively, teachers can problematise terms like 'laws' and 'principles' and guide the students into a discussion that addresses their meaning and significance.

37.3.2 Laws in Chemistry

Until fairly recently, the status of laws in chemistry has received little attention within philosophy of science (e.g. Cartwright 1983). With the upsurge of philosophy of chemistry in the 1990s (Erduran & Mugaloglu, this handbook), there has been more focus on what might (or not) make laws distinctly chemical in nature. Some philosophers of chemistry (e.g. Christie and Christie 2000) as well as chemical educators (e.g. Erduran 2007) have argued that there are particular aspects of laws in chemistry that differentiate them from laws in other branches of science with implications for teaching and learning in the science classroom. A topic of particular centrality and relevance for chemical education is the notion of 'Periodic Law' which is typically uncharacterised as such:

> Too often, at least in the English speaking countries, Mendeleev's work is presented in terms of the Periodic Table, and little or no mention is made of the periodic law. This leads too easily to the view (a false view, we would submit), that the Periodic Table is a sort of taxonomic scheme: a scheme that was very useful for nineteenth century chemists, but had no theoretical grounding until quantum mechanics, and notions of electronic structure came along. (Christie and Christie 2003, p. 170)

A 'law' is typically defined as 'a regularity that holds throughout the universe at all places and at all times' (Salmon et al. 1992). Some laws in chemistry like the Avogadro's Law (i.e. equal volumes of gases under identical temperature and pressure conditions will contain equal numbers of particles) are quantitative in nature while others are not. For example, laws of stoichiometry are quantitative in nature and count as laws in a strong sense. Others rely more on approximations and are difficult to specify in an algebraic fashion. As a key contributor to philosophy of chemistry, Eric Scerri (2000a) takes the position that some laws of chemistry are fundamentally different from laws in physics (Scerri 2000a). While the emphasis in physics is on mathematisation, some chemistry laws take on an approximate nature:

> The periodic law of the elements, for example, differs from typical laws in physics in that the recurrence of elements after certain intervals is only approximate. In addition, the repeat period varies as one progresses through the periodic system. These features do not render the periodic law any less lawlike, but they do suggest that the nature of laws may differ from one area of science to another. (Scerri 2000a, p. 523)

Viewed from the perspective of physics, the status of the periodic system may appear to be far from lawlike (Scerri and McIntyre 1997). Significantly, the periodic law seems not to be exact in the same sense as are laws of physics, for instance, Newton's laws of motion. Loosely expressed, the Periodic Law states that there exists a periodicity in the properties of the elements governed by certain intervals within their sequence arranged according to their atomic numbers. The crucial feature which distinguishes this form of 'law' from those found in physics is that chemical periodicity is approximate. For example, the elements sodium and potassium represent a repetition of the element lithium, which lies at the head of group I of the periodic table, but these three elements are not identical. Indeed, a vast amount of chemical knowledge is gathered by studying patterns of variation that occur within vertical columns or groups in the periodic table. Predictions which are made from the so-called periodic law do not follow deductively from a theory in the same way in which idealised predictions flow almost inevitably from physical laws, together with the assumption of certain initial conditions.

Scerri further contrasts the nature of laws in physics such as Newton's Laws of Gravitation. Even though both the Periodic Law and Newton's Laws of Gravitation have had success in terms of their predictive power, the Periodic Law is not axiomatised in mathematical terms in the way that Newton's Laws are. Part of the difference has to do with what concerns chemists versus physicists. Chemists are interested in documenting some of the trends in the chemical properties of elements in the periodic system that cannot be predicted even from accounts that are available through contributions of quantum mechanics to chemistry. Christie and Christie (2000), on the other hand, argue that the laws of chemistry are fundamentally different from the laws of physics because they describe fundamentally different kinds of physical systems. For instance, Newton's Laws described above are strict statements about the world, which are universally true. However, the Periodic Law consists of many exceptions in terms of the regularities demonstrated in the properties and behaviours of elements. Yet, for the chemist there is a certain idealisation about how, for the most part, elements will behave under particular conditions. In contrast to Scerri (2000a) and Christie and Christie (2000), Vihalemm (2003) argues that all laws need to be treated homogeneously because all laws are idealisations regardless of whether or not they can be axiomatised. van Brakel further questions the assumptions about the criteria for establishing 'laws':

> If one applies "strict" criteria, there are no chemical laws. That much is obvious. The standard assumption has been that there are strict laws in physics, but that assumption is possibly mistaken . . . Perhaps chemistry may yet provide a more realistic illustration of an empirical science than physics has hitherto done. (van Brakel 1999, p. 141)

Christie and Christie (2000) indicate that taking physics as a paradigmatic science, philosophers have established a set of criteria for a 'law statement', which 'had to be a proposition that (1) was universally quantified, (2) was true, (3) was contingent, and (4) contained only non-local empirical predicates' (p. 35). These authors further argue that such a physics-based account is too narrow and applies only to simple systems. More complex empirical sciences do not necessarily conform to such accounts of laws:

> The peculiar character of chemical laws and theories is not specific to chemistry. Interesting parallels may be found with laws and theories in other branches of science that deal with complex systems and that stand in similar relations to physics as does chemistry. Materials science, geophysics, and meteorology are examples of such fields. (Christie and Christie 2000, p. 36)

The debates around the nature of laws in chemistry are ongoing and it is beyond the scope of this paper to contribute to this debate. However, it is important to problematise the complexity in the ways that philosophers of chemistry dispute the nature of chemical knowledge at large and the nature of laws in particular.

In summary, the suggestion offered by Christie (1994) is considered useful:

> Ultimately the best policy is to define 'laws of nature' in such a way as to include most or all of the very diverse dicta that scientists have chosen to regard as laws of their various branches of science. If this is done, we will find that there is not a particular character that one can associate with a law of nature. (Christie 1994, p. 629)

37.3.2.1 The Case of Periodic Law in Chemistry Textbooks

This section describes a case study of how a typical textbook covers the Periodic Table and how the discussion on the nature of the Periodic Law from a philosophical perspective could inform textbook revision. The purpose of this example is to illustrate how the philosophical dimensions of chemistry can be better captured in textbooks so as to ensure understanding of the epistemological aspects of chemistry. The coverage of the Periodic Table in chemistry textbooks has been highlighted to be problematic from a range of perspectives. For instance, Brito and colleagues (2005) argue that the important distinction of accommodation versus prediction in the context of Periodic Table is not covered in chemistry textbooks. In *A Natural Approach to Chemistry*, a textbook that is in current use in secondary schools in the USA, Hsu and associates (2010) dedicate a whole 31-page chapter to 'Elements and the Periodic Table'. The chapter begins with a section on the origin of elements in the universe. There are numerous occasions where the discussion on elements is linked to everyday contexts including the nature of metals on the hull of a boat, the human body and nutrition. A significant portion of the chapter is dedicated to the discussion on electronegativity, ionisation energy, the groups and series in the Periodic Table and an explanation of why compounds form using the Lewis dot notation. The chapter concludes with a set of open-ended and multiple-choice questions.

The coverage of the Periodic Table does mention the notion of patterns but not laws. In the section describing the development of the Periodic Table and the contributions of Dimitri Mendeleev, the authors state that he *'was trying to figure out if there was any kind of organisation to the elements, some kind of pattern he could use to help organize them in a logical way*' (p. 171). This reference is in contrast to the earlier discussion about the approximate nature of the Periodic Law. Indeed, predictions which are made from the so-called Periodic Law do not follow deductively from a theory in the same way in which idealised predictions flow almost inevitably from physical laws. In this respect, the reference to a 'logical way' in the textbook can be misleading in communicating the approximate nature of periodicity. The characterisation of the word 'periodic' is equally devoid of any specification of the approximate nature of the pattern: *'The Periodic Table is named for this because the rows are organised by repeated patterns found in both the atomic structure and the properties of the elements'* (p. 171). The explanation of the Periodic Table in terms of the atomic theory further stresses the logical ordering that the authors are emphasising throughout the text. In the discussion on the Modern Periodic Table, the authors state the following:

> At the time of Mendeleev, nothing was known about the internal structure of atoms. Protons were not yet discovered so the more logical ordering by atomic number was not possible. Today's table includes many more elements, and is ordered not by atomic mass, but by atomic number. However two things are still true of the periodic table, each column represents a group of elements with similar chemical properties, and each row (or period) marks the beginning of some repeated pattern of physical and chemical properties. While elements can be broadly categorized into metals, non-metals, and metalloids, an understanding that

> each column has similar chemical properties had lead to names for some of these element groups. (Hsu et al. 2010, p. 175)

What follows is the quantum mechanical models and the use of orbitals in explaining the organisation of the groups of elements. Considerable discussion is dedicated to establishing the role of valency in explaining periodicity including the introduction of the Lewis dot diagrams. The coverage of this textbook in terms of the viewing of the Periodic Table as a taxonomical tool and a scheme without any explicit emphasis on the character of periodicity as a lawlike feature of chemistry is consistent with observations of Christie and Christie (2003) mentioned earlier.

In his critique of Atkins' chemistry textbook coverage of quantum mechanical explanations, Scerri (1999) highlights a tendency among chemistry textbook writers to ignore the irregularities in the patterns in the Periodic Table:

> One is tempted to protest that in fact the proffered explanation does indeed require a new principle, namely the strange notion whereby the d- and f-subshells do not need to be complete for the shell itself to be classified as complete./…/Surely it would not have detracted from the triumph of science to admit at this point, or anywhere in the book, that the assignment of electrons to particular orbitals is an approximation. In fact, Atkins could have made his story of the Periodic Kingdom all the more interesting if he had stated that even though his discussion was based around an approximate concept, we are still able to use it to remarkable effect to explain so many macroscopic and microscopic features connected with trends in the periodic table. (Scerri 1999, p. 302)

When the textbooks do cover the peculiarities, they are left undiscussed, as exemplified in the textbook mentioned earlier. Consider, for instance, the following excerpt:

> The transition metals illustrate a peculiar fact: the 3d orbitals have higher energy than the 4 s orbitals!/../Energy is the real, physical quantity that determines how the electrons act in atoms. The real energy levels correspond to the rows of the periodic table. The quantum number is an important mathematical construction, but is not the same as the energy level. (Hsu et al. 2010, p. 179)

Here there is a missed opportunity to raise some philosophical insights into the role of empirical evidence in model building in contrast to the mathematical and theoretical grounds for quantum mechanical models in chemistry. Scerri highlights this issue by inviting textbook writers to consider the grounds on which orbital models are related to periodicity:

> In addition, the failure to provide an adequate explanation of the 4 s/3d question or a deductive explanation of the precise places where the elements appear to 'recur' should give us and Atkins grounds for suspecting that this model is not even all that empirically adequate. (Scerri 1999, p. 303)

So what would a revised chemistry textbook look like in light of this discussion so far? There are at least two issues that this coverage of the nature of the Periodic Law raises for consideration in textbook writing. First, the textbooks should elicit the approximate nature of the Periodic Law and specify the reference to the patterns in periodicity as an instance of law while highlighting the difference of interpretations of law in different branches of science. Second, the juxtaposition of the empirical versus theoretical dimensions of the orbital models should be teased out to clarify the different epistemological status of the Periodic Table in light of its historical and empirical foundation versus the incorporation of theoretical and mathematical characterisations since the advance of quantum mechanical models. Erduran (2007) has proposed that an argumentation framework could offer a useful pedagogical strategy for eliciting different characterisations of laws and suggested a potential activity could be structured as follows:

Claim 1: The Periodic Law and the law of gravitation are similar in nature. The term 'law' can be used with the same meaning for both of them.
Claim 2: The Periodic Law and the law of gravitation are different in nature. The term 'law' cannot be used with the same meaning for both of them.

These claims could be presented with evidence that would support either claim, both or neither. For example, the statement 'a law is a generalisation' could support both claims while 'the periodic law cannot be expressed as an algebraic formula while the law of gravitation can be' could support the second claim. The task for the students would be to argue for either claim and justify their reasoning. Further statements can be developed that would act as evidence for either, both or neither claim.

The inclusion of a framework that simulates the philosophical debate on the nature of laws in a comparative context between physics and chemistry will carry into the classroom the ways in which philosophers have conceptualised the nature of this particular aspect of scientific knowledge in these domains. Without a sense of a debate, textbooks reinforce the 'received view' of science that projects a perception of a consensus when there is none. In summary, the inclusion of meta-perspectives offered by philosophical accounts of laws can provide insights into textbook accounts of laws whereby the particular nuances of chemical knowledge are better framed in terms of consistency with epistemological accounts on chemical knowledge.

37.4 The Nature of Explanation in Biology and Chemistry

37.4.1 Explanation in Biology

Explanation in biology differs from explanation in physics in that it does not aim to provide the typical 'necessary and sufficient conditions'. Instead biological explanations aim to 'gain partial, but ever increasing insights into the causal workings of various *life processes*' (Brigandt 2011, p. 262). Mayr's (1961) distinction between proximate explanation and ultimate explanation provides a basic dichotomy between at least two ways of explaining biological systems. In asking about how a phenomenon happens, the proximate explanation would address physiological or other processes that underlie the cause, while the ultimate explanation would address the phenomenon based on the organism's evolutionary history. The explanations do not contradict but rather complement each other by adding a different dimension: one causal and another historical.

Further expansion of explanatory breadth can be found in Tinbergen's (1952, cited in Sterelny and Griffiths 1999) four explanatory projects in biology, according to which it is possible to address questions about any behaviour by proposing 4 different explanations: proximal, developmental, adaptive and evolutionary:

> Tinbergen distinguished four questions we could have in mind in asking why a bittern stands still with its bill pointed directly at the sky. (1) We could be asking for a *proximal* explanation: an explanation of the hormonal and neural mechanisms involved in triggering and controlling this behavior. (2) We could be asking for a *developmental* explanation: an explanation of how this behavior pattern emerges in a young bittern. (3) We could be asking for an *adaptive* explanation: an account, that is, of the role this behavior currently plays in the bittern's life. (4) Finally, we could be asking for an explanation of how and why this behavior evolved in this bittern and in its ancestors. (Sterelny and Griffiths 1999, p. 50)

Press (2009) suggests that one of the ways in which philosophers contrast physics and biology is by appealing to differences between their respective explanations as they relate to the covering law model. He describes divergent views among philosophers of biology, as represented by Sober, Kitcher and Rosenberg regarding the applicability of the covering-law model in the context of biological explanations. After analysing the different positions, Press (2009) concludes that there is a good fit between Hempel's covering law model and biological explanations, stating that 'the differences between biological and physical explanations are merely a matter of degree. …. biologists, who deal with extremely complex systems, will need to rely relatively heavily on various sorts of approximation if they are to explain anything at all' (Press 2009, p. 374).

Branching off of these distinctions, philosophers of biology have detailed a number of explanatory types that support the aim of gaining insights about the 'causal workings' of biological systems without limiting their discussion to causal explanations. Wouters (1995), for example, outlines five different types of explanation: Physiological, Capacity, Developmental, Viability and Historical/Evolutionary. These different types of explanation approach the same phenomena from different perspectives. To explain the circulatory system of a given organism, for example, Wouters argues that physiological explanations focus on the types of events in the individual organism's life history, whereas a capacity explanation focuses on underlying causal explanations having to do with the structure of the heart and valves. A developmental explanation would focus on the development of the system (heart and vessels), while a viability explanation would focus on why structural differences between systems occur in different organisms. Finally, an evolutionary explanation would focus on differences in systems between organisms in the same lineage.

More recently, Wouters (2007) has proposed a sixth type, design explanation, in which a system in a real organism might be compared to a hypothetical one. Calcott (2009) makes the case for an additional type of explanation that he names lineage explanation. This type of explanation aims to make plausible a series of incremental changes that lead to evolutionary change, focusing on a sequence of mechanisms that lead to the successive changes. Lineage explanations 'show how small changes between ancestral and derived mechanisms could have produced different behavior, physiology and morphology' (Calcott 2009, p. 74). Consequently, they provide an additional 'explanatory pattern' to account for evolutionary change.

Rose (2004) offers a fable that supports the discussion of how biological systems can sustain a variety of explanations. In this fable, five biologists are having a picnic when they noticed a frog jump into a nearby pond. Posing the question of what caused it to do so led to five different answers. The physiologist reasoned that impulses travelled from its retina to the brain and then to the leg muscles. The biochemist pointed out the properties of the proteins, actin and myosin, whose fibrous nature enable them to move in a predictable way. The developmental biologist attributed it to the ontogenetic processes that occurred during early stages of cell division. The animal behaviourist attributed the cause to the snake that was lurking by, whereas the evolutionist discussed the role of natural selection in favouring those frogs that escaped their prey due to their ability to detect them quickly and move fast in response, allowing them to survive and reproduce.

Of course, the question of legitimacy of teleological explanation in biology is important because of historical and pedagogical reasons. This is because attributing purpose to non-purposeful things or events or attributing human qualities to nonhumans can lead to questioning the credibility of the proposed explanation. The human tendency to assign purpose to everything seems to be nourished by the 'sheer efficiency of biological structures [which] reinforces the illusion of purpose' (Hanke 2004, p. 145). Use by some biologists in a metaphorical sense makes these explanations likely to be misunderstood by non-experts, especially in educational settings. Some philosophers of biology differ in their degree of opposition to the use of these explanations—perhaps because they are well aware of their semantic affordances and limitations. Few philosophers strongly object to their use as expressed in Hanke's (2004) viewpoint that teleology is 'bad not so much because it's lazy and wrong (which it is) but because it is a straightjacket for the mind, restricting truly creative scientific thinking' (p. 155).

The philosophical debates around these ideas have implications for educational settings but empirical findings can assist in making informed judgments regarding their use in educational contexts. Some science educators have cautioned against the use of anthropomorphic and teleological explanations in biology teaching out of concern for engendering misconceptions that can interfere with learning (Jungwirth 1979). However, a recent study called for the 'removal of the taboo' regarding teleological and anthropomorphic explanations, arguing that results of an empirical cognitive study has shown that high school students' use of anthropomorphic or teleological explanations is not indicative of teleological reasoning but seems to serve a heuristic value for learning as gleaned from the students' perspective (Zohar and Ginossar 1998).

The range of explanations described by Wouters (1995, 2007), Calcott (2009) and Rose (2004) illustrates the significance of invoking a diverse set of explanations for providing more comprehensive understanding of biological systems. Perhaps one of the overarching attributes of biological explanations is the notion of consilience in which different explanations need not be subsumed under one another and need not contradict with one another. The notion of consilience attributed to Wilson by Rose (2004) can perhaps be viewed as a pragmatic adaptation of the notion of 'consilience of inductions' developed by Whewell in his *Novum Organon Renovatum* (Morrison 2000). The diversity of explanatory types in biology is perhaps reflective of the 'epistemological pluralism' (Rose 2004, p. 129) that is characteristic of the study of biological systems. This diversity is often obscured in biology education, not because it is difficult to communicate, but mostly due to the way the school biology curriculum is chopped up and structured in ways that limit reference at a given point in time to one or two explanatory emphases. This in turn limits teachers' and students' ability to experience the value of epistemological pluralism as a powerful vehicle for explaining and understanding phenomena in the life sciences.

37.4.1.1 Explanation in Biology Textbooks

Topics typically covered in high school biology textbooks in the United States include evolution, genetics, cell biology and ecology. The approach to explicating these topics and the order in which they are presented varies significantly from one publisher to another.[5] For example, in the SEPUP (2011) book, the ecology unit, typically presented in other books as the last unit, is second to a first unit on sustainability, a topic rarely addressed so explicitly in biology textbooks. However, explanations in the three textbooks consulted (see footnote) are similar to one another in that they are not differentiated from the rest of the text, but are blended in the narrative, becoming rather 'invisible'. The explanations follow the topical narrative, but there is no discernible attempt to provide a broader synthesis, weave cross-topical themes, or illustrate the notion of explanatory consilience.

37.4.2 Explanation in Chemistry

In the *Stanford Encyclopedia of Philosophy*, Weisberg and colleagues (2011) review the recent developments in the formulation of chemical explanations. These authors state that from the nineteenth century onwards, chemistry was commonly taught and studied with physical models of molecular structure. Beginning in the twentieth century, mathematical models based on classical and quantum mechanics were applied to chemical systems. The use of molecular models has helped chemists to understand the significance of molecular shape (Brock 2000) and aided visual representation of structure and function of matter. One of the key scientific achievements of the twentieth century, the discovery of the double helical structure of DNA,

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[5] The three textbooks reviewed in this section are BSCS (2003), Campbell et al. (2009), and SEPUP (2011).

was possible because of the use of physical models as explanatory tools (Watson 1968). The focus of chemical explanations entered a new phase with the advent of quantum mechanical theories and their applications in chemistry. The notion of 'explanation' in chemistry has centred in key debates involving not only models but also philosophical themes such as supervenience and reduction (Earley 2003) which will be referenced briefly later in the paper.

According to Weisberg and colleagues (2011), while exact solutions to the quantum mechanical descriptions of chemical phenomena have not been achieved, advances in theoretical physics, applied mathematics and computation have made it possible to calculate the chemical properties of many molecules very accurately and with few idealisations. This perspective is in contrast to those chemists who argue for employing simple, more highly idealised models in chemistry, which stem from the explanatory traditions of chemistry. In developing this point, Hoffmann illustrates two modes of explanation that can be directed at chemical systems: horizontal and vertical (Hoffman 1998). Vertical explanations are what philosophers of science call 'deductive-nomological explanations'. These explain a chemical phenomenon by deriving its occurrence from quantum mechanics. Calculations in quantum chemistry are often used to make predictions, but insofar as they are taken to explain chemical phenomena, they follow this pattern. By showing that a molecular structure is stable, the quantum chemist is reasoning that this structure was to be expected given the underlying physics.

In contrast to the vertical mode, the horizontal mode of explanation attempts to explain chemical phenomena with chemical concepts. For example, Weisberg and colleagues (2011) use the example of SN_2 reactions as an example of horizontal explanations. The first year organic chemistry curricula include the relative reaction rates of different substrates undergoing SN_2 reactions. They state that an organic chemist might ask 'Why does methyl bromide undergo the SN_2 reaction faster than methyl chloride?' One answer is that 'the leaving group Br^- is a weaker base than Cl^-, and all things being equal, weaker bases are better leaving groups'. This explains a chemical reaction by appealing to a chemical property, in this case, the weakness of bases. Vertical explanations demonstrate that chemical phenomena can be derived from quantum mechanics. They show that, given the (approximate) truth of quantum mechanics, the phenomenon observed had to have happened. Horizontal explanations are especially good for comparing and contrasting explanations, which allow the explanation of trends. In the above example, by appealing to the weakness of Br^- as a base, the chemist invokes a chemical property. This allows the chemist to explain methyl bromide's reactivity as compared to methyl chloride, and also methyl fluoride, methyl iodide and so on. Insofar as chemists want to explain trends, they make contrastive explanations using chemical concepts.

Apart from Hoffmann, earlier chemists argued that the nature of chemical explanations need not be overshadowed by quantum mechanical and reductive approaches. Consider, for instance, the perspective taken by Coulson:

> The role of quantum chemistry is to understand these concepts and show what are the essential features in chemical behavior. [Chemists] are anxious to be told … why the H–F

> bond is so strong, when the F–F bond is so weak. They are content to let spectroscopists or physical chemists make the measurements; they expect from the quantum mechanician that he will explain why the difference exists. … So the explanation must not be that the computer shows that [the bonds are of different length], since this is not an explanation at all, but merely a confirmation of experiment. (Coulson 1960)

Although both Coulson (1960) and Hoffmann (1998) defend the use of simple, idealised models to generate horizontal explanations, it is not clear that quantum calculations can never generate contrastive explanations (Weisberg et al. 2011). Although single vertical explanations are not contrastive, a theorist can conduct multiple calculations and, in so doing, generate the information needed to make contrastive explanations. However, the status of quantum mechanical explanations in chemistry is likely to be challenged for some time yet to come given the history of chemists' position on this issue. For example, Brown (2003) has drawn from cognitive sciences to illustrate that chemical explanations are metaphorical in nature and have a character that is distinguishable from representations employed in other fields of science: '…data are not explanatory in themselves. For the chemist to make effective use of powerful computational resources there must still be an underlying metaphorical model of what is happening in the conventional (chemical) sense' (p. 216). Even though chemical explanations involve the use of models and modelling (Erduran 2001), the meaning of the term 'model' or its function is not so straightforward particularly in relation to its import in chemical education. The presence of models in different disciplines related to chemical education, such as cognitive psychology and philosophy of science, makes it even more difficult to come up with a single definition for the term 'model' (Erduran and Duschl 2004).

A particular approach to chemical explanations includes the reference to 'structural explanations' (Harré 2003). Goodwin (2008) explains that in organic chemistry, the phenomena are explained by using diagrams instead of mathematical equations and laws. In that respect, the field of organic chemistry poses a difference in terms of the content of explanations from those in other physical sciences. Goodwin investigates both the nature of diagrams employed in organic chemistry and how these diagrams are used in the explanations. The diagrams particularly mentioned are structural formulas and potential energy diagrams. Structural formulas are two-dimensional arrangements of a fixed alphabet of signs. This alphabet includes letters, dots and lines of various sorts. Letters are used as atomic symbols, dots are used as individual electrons, and lines are used as signs for chemical bonds.

Structural formulas in organic chemistry are mainly used as descriptive names for the chemical kinds. Thus, a structural formula has a descriptive content consisting of a specification of composition, connectivity and some aspects of three-dimensional arrangement. Structural formulas are also used as models in organic chemistry. For example, a ball and stick model is used in explanations. After characterising some features of structural formulas, Goodwin presents a framework of explanations in organic chemistry and describes how both structural formulas and potential energy diagrams contribute to these explanations. Then he gives the examples of 'strain' and 'hyperconjugation' to support his idea about the role of diagrams in capturing the nuances of explanations through structures in organic chemistry.

Debates on reduction—i.e. 'reduction of axioms or laws of one science to the axioms and laws of a deeper putative science' (Scerri 2000b, p. 407)—have taken chemical explanations to its core in understanding what makes an explanation 'chemical'. Similar debates on reductionism have centred on issues related to philosophy of mind, particularly in the context of Multiple Realisability (e.g. Fodor 1974). Educational applications of such debates have been promoted though not yet realised at the level of schooling (e.g. Erduran 2005). One aspect of this debate has concerned the notion of supervenience. Two macroscopic systems that have been constructed from identical microscopic components are assumed to show identical macroscopic properties, whereas the observation of identical macroscopic properties in any two systems need not necessarily imply identity at the microscopic level. Chemical explanations have often been regarded as including microscopic, macroscopic and symbolic dimensions (e.g. Jacob 2001). The main position promoted in this debate is that the asymmetry in the way that properties and kinds of chemical entities are conceptualised suggests that chemical explanations cannot necessarily be reduced to explanations of physics—a realm of epistemology—even if ontologically chemistry might be reliant on physical principles.

37.4.2.1 Explanation in Chemistry Textbooks

Kaya and Erduran (2013) believe that structural explanations as discussed by Goodwin (2008) have relevance for chemistry textbooks. In their study of secondary chemistry textbooks across grade levels, they noted, for example, that for the 9th grade textbooks, topics such as 'development of chemistry', 'compounds', 'chemical changes', 'mixtures' and 'chemistry in our life' all included structural explanations. Similar ways of coverage are noted in the textbook by Hsu and colleagues (2010). In the chapter on organic chemistry, for example, there are sections that illustrate and define 'structural isomers'. The Appendix depicts the textbook reference to structural isomers of 2-pentane and isopentane. The description is 'When a molecule has the same number and type of atoms, but a different bonding pattern, it is a structural isomer' (p. 541). The rest of the text is similar in terms of providing definitions for the characterisation of isomers. There are two types of representations that are both two-dimensional but one represents the C and H atom balls, while the other does not. In this sense, there is potential for confusion for what counts as 'structure' when different levels of representations are superimposed.

37.4.3 Summary

This paper focused on the context, the definitions and the types of laws and explanations in biology and chemistry and described some emphases and patterns that illustrate a number of similarities and differences between biological and chemical laws and explanations. For example, when the types of explanation in chemistry and biology are contrasted, the result is a diversity of types that are distinctive to the science in question. While biological explanations include viability and developmental explanations that draw closely from the nature of biological content, chemical explanations focus on the structural and representational explanations that are based on either quantum mechanical or simple chemical models. The context of debates around the nature of biological and chemical laws and explanations are also rather particular. Whereas reference to principles is common in biologists' discussions of laws, the chemists are preoccupied with questions regarding axiomatisation and approximation.

37.5 Implications for Biology and Chemistry Education

This section provides some suggestions for how biology and chemistry education can be informed by investigations into the nature of laws and explanations. It illustrates the implications of the preceding discussion for teaching, curriculum and learning in biology and chemistry education. Design of instructional activities can exemplify more explicitly the role that variation and chance play in biological systems and enable students to explore the contribution of this uniqueness to shaping the formulation of biology's 'laws' or principles. Awareness of the function of generalisations and principles in biology allows students to appreciate their role in the construction of biological knowledge and enables them to realise that the scarcity of 'laws' does not diminish the 'power' of the generalisations/principles they study or reduce the status of biology to a 'soft science'.

In terms of chemistry teaching, the goals of teaching could include the broader aims of promoting students' understanding of how some chemical laws like the Periodic Law are generated and how they differ from laws in chemistry or other sciences. Lesson activities could acknowledge the observation that, for instance, the Periodic Law will be manifest in the classroom via comparative discussions about the trends in the chemical and physical properties of elements. Furthermore, engaging students in the process of the derivation of some of these trends is likely to give them a sense of how laws are generated and refined in chemistry. How can such discussions of laws, then, be manifested in the classroom? Earlier work has identified strategies such as questioning and discussion in chemistry teaching (Erduran 2007) that can be extended to biology teaching due to their broad pedagogical scope. For example, students could be presented with alternative accounts of scientific laws—those derived deductively and those that are derived with approximation and induction in mind—and asked to question, compare, evaluate and discuss them in relation to other products of scientific knowledge.

This review also has implications for the design of curricula for the inclusion of biological and chemical content knowledge. With respect to biology, curriculum materials should attempt to communicate more explicitly elements of 'epistemological pluralism' and how biologists search for consilience among a proposed family of explanations. Including these ideas in the curriculum should not be limited to presenting isolated narratives about how biologists work but should be reflected in developing more integrated and coherent content frameworks. This is necessary for promoting a more holistic and contextual understanding of structures and processes in biotic systems. Even though the chemistry curriculum typically covers structural explanations as described by Goodwin (2008) across various levels of schooling, the meta-perspectives on the nuances of these explanations are not typically part of either curriculum materials or textbooks (Kaya and Erduran 2013).

The discussion about the power and limits of biological and chemical laws can be initiated in curriculum resources by focusing more explicitly on what Mendel's Laws or the Periodic Law do and fail to do. Curricula and textbooks tend to cover laws in quite an ambiguous and limited manner (i.e. McComas 2003) and often present laws in different science fields on equal footing. That is, when certain generalisations are labelled as laws, textbook authors do not contextualise or explore what that label means. From the point of view of a teacher or student, a law in physics (e.g. Newton's) carries the same epistemic and ontological significance as a law in biology (e.g. Mendel's) or chemistry (e.g. Periodic). In some cases, neither Mendel's Law nor the Periodic law is introduced as laws, and consequently an opportunity to discuss the implications of these terms is lost. A study of Turkish chemistry curricula and textbooks, for example, revealed that there is little or no differentiation of the meta-perspectives on the nature of knowledge (Kaya and Erduran 2013). Other studies on textbooks (e.g. Niaz and Rodríguez 2005) point to the lack of attention to NOS features in general, let alone the nuanced distinctions addressed here. Understanding the relationship of laws and explanations to theories in biology and chemistry demands a deliberate undertaking from historical and contemporary perspectives.

Furthermore, chemistry curricula often contain conceptual mistakes and thus demand closer examination. For example, the notion 'one molecule, one shape' is widespread and results in students' construction of a misconception where molecules are static, not oscillating and taking on different shapes (Kaya and Erduran 2013). The dynamic nature of molecular shape is an inherent aspect of chemical explanations. Coverage of structural explanations with meta-level perspectives is likely to minimise misconceptions about the dynamic nature of molecules. Chemistry curricula also need to scaffold students' understanding of how chemical explanations can rest on structural models and how these differ from, for instance, historical or evolutionary explanations in biology. Design of instructional activities would, then, need to acknowledge the observation that explanations will be manifest in the classroom via discussions of the signs and symbols that make up the alphabet of structures represented in chemistry. Engaging students in the generation, evaluation and application of structural explanations in chemistry is likely to improve their understanding of how chemical language and explanation relate to each other.

There are important reasons for why biology and chemistry learning should be informed by the issues raised in the paper. Familiarising students with different *types* of explanation in biology may mitigate against straying into teleological sidetracks, favouring the capacity/causal type, or privileging some types of explanation over others (those dealing with the how over those dealing with the why). The tendency of students to favour experimental over historical explanations, for example, has been documented in the context of evolutionary theory (see, for example, Dagher and BouJaoude 2005). Thus, biology learning could focus on constructing and utilising a broad range of biological explanations for a given phenomenon and applying this kind of reasoning to multiple contexts/phenomena. In support of this kind of learning, there needs to be a restructuring of the content/curriculum, so that explanations addressing different aspects of the phenomenon under study are not isolated from each other as is typically the case (e.g. evolutionary and ecological concepts are rarely discussed in relation to each other or to physiological concepts in school science). With respect to chemistry learning, the articulation of structural explanations with meta-level perspectives is likely to assist in understanding the dynamic nature of molecules. As discussed earlier, a common problem in chemical education concerns the interpretation of molecular models and straying onto static notions of molecular structures as sidetrack in learning outcomes. Given the centrality of molecular structure and modelling in chemistry, improvement in the learning of the structural explanations is likely to have positive impact on understanding other related areas of chemistry.

37.6 Conclusion

In summary, the aspects of laws and explanations in biology and chemistry emphasised in this paper are not exhaustive but are representative of the types of issues that concern us as science educators interested in improving students' understanding of science. This understanding will be enriched if students are provided multiple opportunities to develop meta-level understanding of how particular domains of science engage with some of the key aspects of scientific knowledge such as laws and explanations. There has been a long-standing criticism of science education in failing to enable students to understand the nature of science, scientific knowledge and scientific knowledge development. While science educators have acknowledged that perspectives from history and philosophy of science can promote a deeper understanding of the nature of science, the role of the nature of disciplinary knowledge has been under-investigated within the science education research community. The aim of this chapter was to articulate the nature of laws and explanations in biology and chemistry so as to extend and enrich the previous agendas for teaching the nature of science using domain-specific epistemologies to describe key debates and features related to disciplinary knowledge. Further research in this area is needed to further clarify, refine, challenge and expand some of the claims presented in this paper.

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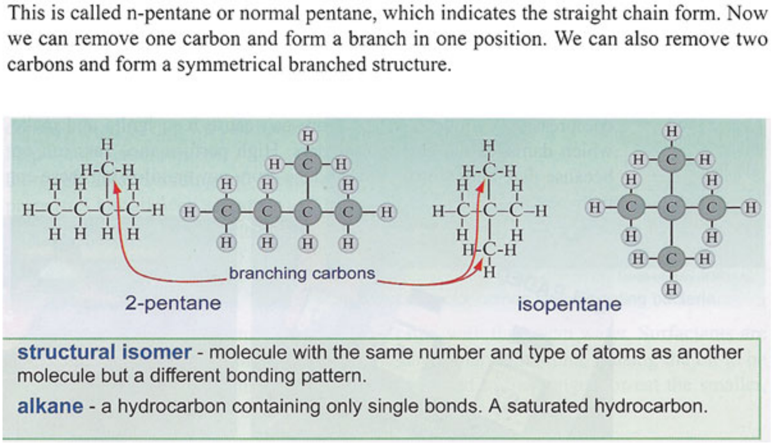
Appendix

Source of potential confusion about structural explanations in a high school chemistry textbook (Reproduced from Hsu et al. 2010, p. 541).


This is called n-pentane or normal pentane, which indicates the straight chain form. Now we can remove one carbon and form a branch in one position. We can also remove two carbons and form a symmetrical branched structure.

structural isomer - molecule with the same number and type of atoms as another molecule but a different bonding pattern.

alkane - a hydrocarbon containing only single bonds. A saturated hydrocarbon.

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Chapter 38
Thought Experiments in Science and in Science Education

Mervi A. Asikainen and Pekka E. Hirvonen

38.1 Introduction

When Albert Einstein was 16, he considered the following thought experiment. He imagined chasing after a beam of light with the velocity of c. He would then catch the light wave and be moving with it and the light wave would seem to be frozen. Einstein noted both his experiences and Maxwell's electromagnetic theory, which suggests that such a stationary wave does not exist. In addition, he noted that if an observer were to see him riding on a light wave with a velocity of c, Einstein himself would not be able to observe the velocity.

This example illustrates the essence of a thought experiment.[1] The thought experiment describes an imaginary, hypothetical situation. The thought experiment cannot always be performed as a physical experiment, in this particular case, because it is impossible for such a massive object (Einstein) to have the velocity of c. In several respects, however, the thought experiment resembles a physical experiment. Its premise of c as the velocity of light is an empirically measured theoretical result using Maxwell's theory of electromagnetism as a starting point. It rests on the hypothesis of riding a light wave, which inevitably fails as a result of the empirical observations and impossibilities contained in theories associated with physics.

The purpose of what follows in this chapter is to examine the role of thought experiments in science and science education. First, different definitions of the concept of thought experiment will be discussed. Second, it will be argued that TEs form an essential part of scientific methodology, a special case of scientific experimentation. Third, attention will be paid to the role played by TEs in the

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[1] A scientific experiment can be either a thought experiment performed in thought or a physical experiment performed in the laboratory.

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development of scientific theories. Subsequently, attention will also be paid to the pedagogical benefits of the use of thought experiments in science learning and the reported studies on the use of thought experiments in science teaching. It will be argued that, as a result of the various benefits of TEs, their use should be increased in science teaching. Finally, our discussion will focus on the challenges posed by TEs in the teaching and learning of science.

38.2 Descriptions of the Concept of the Thought Experiment

Thought experiments have a long history, starting from the time of pre-Socratics (Rescher 1991; Brown and Fehige 2010). It has been argued that during the Middle Ages, thought experimenting was one of the main methods used in science (King 1991). In the seventeenth century, Galileo Galilei and Isaac Newton used thought experiments (TEs) as part of their scientific methodology.[2] The rise of relativity and quantum physics would not have been possible without thought experiments, and famous thought experimenters include Niels Bohr, Erwin Schrödinger, and Albert Einstein (Brown 1986; Matthews 1988; Zeilinger 1999).

Modern science philosophers and scientists have attempted to frame a general description of the concept of thought experiment (TE). Roy A. Sorensen (1992) sees TEs in a broad light: the only difference between an actual experiment and a thought experiment is that a thought experiment attempts to achieve its aim without the benefit of actual implementation. However, as Galili (2009) has criticised, Sorensen's definition of an experiment goes beyond the realm of science. According to Sorensen, a scientific experiment is “a procedure for answering or raising questions about the relationship between variables by varying one (or more) of them and tracking any response by the other or others”. Galili states that physical experiments are based on certain theoretical assertions and this is how TEs are also used in science.

Sören Häggqvist (1996) claims that philosophers and scientists often see TEs as something different from “genuine”, “actual”, or “real” experiments but rather as or a species of experiments similar to “laboratory experiments” or “cyclotron experiments”. He characterises a TE loosely as an experiment that aspires to test some hypothesis or theory: it is performed in thought, but paper or pencil, encyclopedias, or computers may also be used (Häggqvist 1996, p. 15).

According to Irvine (1991, pp. 158–159), TEs have to possess at least several, if not all, of the characteristics of a scientific experiment. This means that not all varieties of hypothetical reasoning concerning the natural world can be considered to be TEs. A TE has to bear a special relationship both to previous empirical observations and also to the background theory of TE. A thought experiment cannot ever

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[2] See, e.g. Newton (1728), Newton (1863), Gendler (1998), Palmieri (2003), Palmier (2005), Hall (2000), and Norton (1991).

replace observations or a physical experiment because a thought experiment rests on auxiliary presuppositions considered to be true but whose failure changes the result of the thought experiment per se.

Nancy Nersessian's view of TEs differs slightly from the views presented above in that she sees a TE as a mental model that enables the dissemination of a possible physical event that is often unrealisable in one's imagination (Nersessian 1989, p. 175). Nersessian claims that Galilei, for instance, acted in this way in the case of his TE concerned with falling bodies. According to Nersessian (1992, p. 27), mental simulation is needed for a thought experiment to be both thought and experimental. The original scientific thought experiment is executed by a scientist who imagines a sequence of events and constructs a mental model. Then she/he constructs it in a narrative form in order to describe the thought experiment to others.[3]

Nersessian's view is fascinating because it makes a connection between thought experiments and mental models. On the other hand, the connection makes her definition somewhat complicated because there is no consensus about how individuals possess their knowledge. Is it in form of models (Nersessian 1989, 1992; Nersessian and Patton 2009), "in pieces" (di Sessa et al. 2004; diSessa and Sherin 1998; diSessa 2002), or as coherent and organised naive theories related to particular topics (Vosniadou 1994; Vosniadou et al. 2008)? Some researchers even think that a mental model is an individual's inner, private model that cannot be expressed exactly; when an individual presents his/her model to an audience, the model is not a mental model but *an expressed model* (Gilbert et al. 1998).

Having analysed several definitions of thought experiment, Igal Galili proposes the following definition: "Thought experiment is a set of hypothetico-deductive considerations regarding phenomena in the world of real objects, drawing on a certain theory (principle or view) that is used as a reference of validity" (Galili 2009, p. 12).

Galili's (2009) definition is not concerned with the reality existing outside scientific theories, and it also excludes a pure, formal analysis manipulating with theoretical entities without addressing the real objects. The definition includes scientific TEs that are part of the scientific process and excludes philosophical TEs. Even if we mostly agree with Galili's definition, we do not think that phenomena should be restricted to include only the world of real objects because that would exclude from the definition Maxwell's demon or hypothetical entities, for instance, whose existence cannot be verified. The definition of a thought experiment should also include a more explicit statement about its mental implementation. In sum, TEs are an essential part of scientific methodology, a special form of scientific experiments. Like other scientific experiments, they are based on a particular background theory. The main difference between physical experiments and TEs is that TEs are performed in thought. In addition, TEs can also be devised with hypothetical entities that have not yet been verified or cannot even be verified at all.

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[3] Racher Cooper (2005) and Tamara Szabó Gendler (1998, 2004) are also supporters of this kind of mental model account.

38.3 The Role of Thought Experiments in Science

Ernst Mach and Pierre Duhem were the first to consider the value of thought experiments in science. According to Mach, thought experiments are needed because they precede physical experiments by preparing for their actual implementation (Mach 1976). Duhem's view is the opposite: he considered thought experiments useless because they cannot be presented in symbolic form and hence they cannot replace scientific experiments (Duhem 1990).

Mach (1976) stated that the possibility of a thought experiment rests on our mental images, which are more or less copies of facts. When reminiscing, we may even find new properties of the physical facts that we had not noticed previously. Our mental images are easier and faster to use than the physical facts. Thus, it can be said that thought experiments precede physical experiments and prepare for them. This means that every experimenter has to be aware of the details of the experiment before its actual implementation.

Mach thought that if thought experiments are reported sincerely, they will be true even if two thought experimenters report different sequences. In addition, errors can only occur when the results of thought experiments are compared with the physical reality. Sorensen (1992) argues that Mach's account overemphasises the subjectivity of a thought experiment. Sorensen considers that thought experiments can also be fallacious in their reporting phase.

Sorensen also argues that if a TE always precedes a physical experiment, the concept of the thought experiment has to be so wide that it covers "any kind of forethought about an experiment". He thinks that it is not normal in science to perform the full experiment in thought, but the mental processing is more like the planning stage of a physical experiment. We agree with Sorensen with regard to both of his arguments. Thought experiments conducted by two different thought experimenters can lead to different results in the first stage of TEs, and as often as not they cannot both be true. In addition, experimental scientists undoubtedly plan their physical experiments mentally, but these thoughts are frequently more like schemes of action rather than being full thought experiments.

Mach argues that in some cases, the result of a thought experiment can appear so sure and final that its implementation as a physical experiment may even seem unnecessary (Mach 1976). Duhem sees the role of thought experiments differently than Mach. He considered that thought experiments could not replace physical experiments and that they should be forbidden in science and in science teaching (Duhem 1990). Duhem alleged that only mathematical argument was precise and unambiguous, while the language of concrete observation is not: "The facts of experience, in all their native brutality, cannot be used in mathematical reasoning. To feed such reasoning they must be transformed and put into symbolic form". Duhem's view is sometimes termed sceptical objection (see Brown and Fehige 2010).

This kind of sceptical view of thought experiment is not common amongst science philosophers, but critical views of thought experiments can be found (see, e.g. Brown and Fehige 2010). Hull (1998, 2001) argues, for instance, that TEs are nothing but simple illustration and they end up persuading people; but TEs often contain deficiencies, such as incoherence and missing details. Norton (2004b) agrees with Hull over the fallibility of TEs. In addition, he claims that TEs are simply arguments, and hence they cannot offer any kind of special information that could not also be uncovered by conventional argumentation.

Cooper (2005) argues that thought experiments are needed for several reasons. Some thought experiments are practically possible to implement as physical experiments, but there may be sound reasons (ethical reasons, e.g. or the monetary expense of physical experiment) for performing them only in the mind. Other thought experiments may be impossible to implement as real experiments because they involve idealisations. Cooper (2005, p. 344) argues that Galileo's TE demonstrating that bodies continue moving with constant velocity in the absence of a force – a ball rolling in a frictionless U-bend – includes an idealisation. In science, the idealisations are often similar to the limiting case imposed by extrapolation of the results of the physical experiment. Other thought experiments may be impossible to implement as real experiments because they involve the violation of a physical law. According to Cooper, these TEs resemble the computer simulations that scientists run to discover how phenomena may behave if the laws of nature are slightly different. Cooper states that simulations and thought experiments that cannot be implemented as physical experiments can nevertheless be used as potential sources of knowledge in science.

Buzzoni (2009) claims that thought experiments and real-world experiments form a dialectical unity: without thought experiments there would be no real experiments because we would not know how to ask about their nature, and without real experiments we would not find answers to these questions. According to Galili (2009), thought experiments play a heuristic role. They are free from the constraints imposed by reality (heat, friction, etc.), and the thought experimenter can also forget the technical restrictions (equipment, costs, availability, etc.). In a sense, a person conducting a thought experiment mentally models theoretical physics (Peierls 1980).

From the above it follows that a thought experiment is a special case of scientific experiment that can precede a physical experiment and help the experimenter to conduct it. In some cases, a physical experiment may not be possible and TE may then be the only way to experiment. TEs can also be used to idealise complex physical situations and remove constraints imposed by reality. The physical experiment may either confirm the results of a TE or show that the TE was fallible; both types of TEs are important in constructing an understanding of scientific knowledge. This view of thought experiments can then be used as a starting point in science teaching.

38.4 The Epistemological Role of Thought Experiments in Science

If we approve of TEs as one special part of scientific methodology, we need also to discuss whether TEs play a special epistemic role in the knowledge construction processes of science. The theoretical framework of TEs is of great importance because it determines the image of the nature of science that TEs convey when used in science teaching.

There are two different views of the epistemological status of TEs. The argument-based view states that knowledge comes only via sensory experiences, while the intuition-based (Platonic) view argues that TEs provide information beyond our senses. The argument-based views rely on the idea that TEs can be reconstructed as arguments or that they function via their connection to arguments, so they are unable to provide more information than argumentation in general. On the other hand, the intuition-based view argues that a special group of TEs, Platonic thought experiments, go beyond our senses to acquire a priori information about nature.

38.4.1 Argument-Based Views

Argument-based views rely on the idea that TEs are unable to provide more information than argumentation in general. The supporters of the argument-based view do not mean that TEs are meaningless in science; rather, they are meaningless in an epistemological sense.

John Norton is probably the best-known supporter of the view that thought experiments are basically arguments. He thinks that TEs are not epistemic wonders, but they do tell us about our world using our normal epistemic resources[4] (Norton 1996, 2004a). Norton (1996, p. 339) has formulated his claim in a more precise form, referred to as a *Reconstruction Thesis*, as follows:

> *Reconstruction Thesis:* All thought experiments can be reconstructed as arguments based on tacit or explicit assumptions. Belief in the outcome-conclusion of the thought experiment is justified only insofar as the reconstructed argument can justify the conclusion.

TEs draw on hypothetical and counterfactual situations that essentially separate them from physical experiments (Norton 1991, 1996). These unnecessary particulars are needed for the experimental nature of thought experiments; without them, TEs would not be experimental. These particulars can be psychologically useful, but they are unnecessary for the thought experiment itself.

Norton claims that the epistemological potential of TEs is the same as that of argumentation, since every TE can be reconstructed as an argument (Norton 2004a, b). Because TEs do not involve new empirical data, they can only reorganise or generalise the old data (Norton 1991, p. 335). This prior knowledge, based on our previous experiences, can enter into thought experiments as assumptions. Hence, thought experiments are devices that reorganise or generalise these assumptions to achieve the result of the thought experiment. Norton regards these “devices” as arguments.

If the TE simply reorganises, it is a *deductive* argument or a *reductio ad absurdum* argument, where the particular conclusion follows deductively from the premises.

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[4] Epistemic recourses are processes and tools that we use to decide that we know something or to create knowledge (Redish 2004, p. 31).

For instance, thermodynamics includes some powerful TEs because the first, second, and third laws of thermodynamics can be formulated as "assertions of impossibilities" (Norton 1991, p. 131). The first law can be expressed as an assertion as follows: "It is impossible to design a perpetual motion machine of the first kind, that is, a machine whose sole effect is to produce more energy than it consumes". Norton explains that consequences can be derived from the assertions included in a *reductio* argument, which then almost automatically becomes a thought experiment.

If the TE generalises on a wider scale, it is an *inductive* argument. This kind of TE includes an inductive step that frees the conclusion of its particulars. Norton (1991) suggests that Einstein's magnet and conductor and Einstein's elevator thought experiments belong to this class. According to Norton (1991, p. 137), Einstein's elevator can be constructed as arguments as follows:

1. In an opaque chest, an observer will see free bodies move identically in the case where the box is uniformly accelerated in a gravitation-free space and where the box is at rest in a homogenous gravitational field.
2. Inductive step: (a) the case is typical and will hold for all observable phenomena and (b) the presence of the chest and observer are inessential to the equivalence.
3. A uniformly accelerating frame in gravitation-free space and a frame at rest in a homogenous gravitational field are observationally identical but theoretically distinguished, which is self-contradictory.
4. The verifiability heuristic for theory construction (version 2[5]).
5. A uniformly accelerating frame in a gravitation-free space and a frame at rest in a homogenous gravitational field are the same thing (which becomes a postulate of a new theory).

According to Norton, the inductive step (2), which proceeds from a finite number of specific facts to a general conclusion, is quite problematic but "masked by the thought experiment format". He continues: "The extension from the motion of bodies in free fall to arbitrary processes is quite a leap, especially in view of the bizarre consequences that follow". Based on this example, it seems that constructing a thought experiment as arguments may also contain challenging phases that may not be unambiguous.

Brown and Fehige (2010) present three objections to Norton's claims. First, they consider Norton's view too vague. Second, they argue that Norton reaches far ahead of established facts: every real-world experiment can be represented as a thought experiment but nobody claims that thought experiments are unnecessary. Furthermore, Norton's view does not tell where the arguments come from. Brown and Fehige (2010) admit that a thought experiment can be an essential phase in the building of Nortonian reconstruction, but a thought experiment expressed as an argument loses its power. Arthur (1999) also disagrees with Norton by arguing that

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[5] States of affairs that are not observationally distinct should not be distinguished by the theory (Norton 1991, p. 135).

if TEs are constructed as arguments, there will be an epistemic loss: the original thought experiment is not epistemically similar to the constructed arguments.

Nersessian (1992, p. 27) argues that a Nortonian reconstruction cannot be performed before the actual thought experiment has been executed. This means that TEs really have experimental power. By claiming that a TE contains particulars irrelevant to the conclusions, Norton fails also to see the constructive function of the narrative form in which thought experiments are presented.

Häggqvist (1996) claims that thought experiments are not arguments because something that is a process, an event, or a procedure cannot, by its nature, be an argument; TEs function, however, via their connection with arguments. He argues that thought experiments work in the same way as experiments in general, by affording premises for their associated arguments. For a successful experiment, the premises are true. Only arguments as truth-valued, linguistic entities matter when the truth-value of a scientific or philosophical theory or hypothesis is evaluated.

The argument-based view of TE as presented by Norton (1991, 1996, 2004a, b) seems to be problematic with regard to its potential use in science teaching. The reconstruction process, in particular, would be rather demanding for students because, in practice, students would already need to understand the original TE quite well in order to be able to perform the reconstruction. This does not mean that we do not appreciate the basic skills of scientific argumentation that constitute important learning goals in science education. The argument view may, however, be useful for science educators and science teachers in regarding the nature of the counterpoint of the argument-based view, i.e. Brown's destructive and constructive TEs, which will be examined next.

38.4.2 Brown's Destructive and Constructive TEs

James Robert Brown (1991) classified TEs according to their role in building scientific theories as destructive and constructive TEs. *A destructive TE* is an argument against a theory; it destroys or at least indicates serious problems in the particular theory. According to Brown, Einstein's chasing the light beam, presented in the introduction to this chapter, and Schrödinger's cat are examples of this kind of TE. Erwin Schrödinger presented a cat paradox where a cat in a box exists in a superposition of two states: dead and alive (Schrödinger 1935). His aim was to question the limitations and conceptual difficulties of quantum mechanics.

In contrast, *constructive* TEs break down into three further types: *direct*, *conjectural*, and *meditative* TEs. *A meditative TE* helps in the drawing of a conclusion from a specified, well-articulated theory. It may illustrate some counter-intuitive aspects of the theory, making it seem more satisfying, or it may act like a diagram in a geometrical proof that helps to support understanding, or even in the discovery of, the formal proof. Brown uses Maxwell's demon as an example of meditative TE.

The demon sits between the chambers of a gas vessel, which are filled with gas. The demon opens a trapdoor between the chambers by allowing the faster molecules to move to one side and the slower molecules to the other side. The TE shows that if this kind of demon existed, it would decrease the entropy of the gas system and cause a violation of the second law of thermodynamics. James Clerk Maxwell used this thought experiment to discuss the second law of thermodynamics at molecular level and to show that it possessed only statistical certainty (Schlesinger 1996; Radhakrishnamurty 2010). According to Schlesinger, Maxwell's intention was to use the demon to dramatise his claim concerning the statistical nature of thermodynamics.

A *conjectural TE* establishes some phenomenon and hypothesises a theory to explain the theory thereafter. The events of conjectural TEs have a presumed explanation. A *direct TE* begins with an unproblematic phenomenon and ends with a well-articulated theory. Brown considers Newton's bucket to be a prime example of a conjectural TE. Newton suggested that the existence of absolute space could be substantiated by hanging a bucket of water from a rope and spinning it. The concave shape of the water's surfaces caused Newton to assume that it was spinning with respect to something. Furthermore, according to Brown (1991), Stevin's inclined plane[6] and Einstein's elevator[7] belong to this class of TEs.

A small group of TEs are both destructive and constructive at the same time. These thought experiments are termed Platonic TEs (Brown 1991, p. 34). According to Brown (1991), in a few special cases we may go well beyond existing data to obtain a priori information about nature. Brown and Fehige (2010) explain that this information is a priori information about nature since, because the thought experiment does not contain new information, the conclusion does not draw on old data and it is not some sort of logical truth. This view of thought experiments can be further developed by combining a priori epistemology to recent views about the laws of nature, according to which laws consist of objectively existing relations between abstract entities. This view is, therefore, Platonic.

According to Brown, Galileo's free fall and the EPR (Einstein, Podolsky, Rosen) paradox may be regarded as examples of Platonic TEs. Brown argues that Galileo's free fall extinguished Aristotle's view and generated a new view, while EPR seriously challenged the Copenhagen interpretation and established the incompleteness of quantum mechanics. Brown and Fehige (2010) have characterised Brown's view as an intuition-based view.[8]

Galileo's free fall TE indeed revealed an inconsistency in the Aristotelian view, but it could not say anything about the actual descent of objects, which indeed fall at different rates of acceleration relative to the ground. According to McAllister (2004), Galileo's TE merely verified that if the rate of fall of simple and compound bodies was simply a function of their mass, then the rate of fall of bodies would be

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[6] Stevin's TE discusses the forces that are needed to keep a weight on an inclined plane (see, e.g. Gilbert and Reiner 2000).

[7] If a man is in a windowless elevator, he cannot tell whether the sensation of weight is due to gravity or acceleration.

[8] Intuition can be defined as a capacity for attaining direct knowledge or understanding without the apparent intrusion of rational thought or logical inference (Sadler-Smith and Shefy 2004).

independent of mass. This is an important point that needs to be grasped in physics education (Lehavi and Galili 2009). Hence, Galileo's free fall TE is not actually a Platonic TE. Furthermore, Albert Einstein, Boris Podolsky, and Nathan Rosen attempted to show that quantum mechanics is incomplete, but, instead, a definition of nonlocality was found (Einstein 1918). Quantum mechanics is, however, generally regarded as complete. Bokulich (2001) has discussed both the essence and also further modifications of EPR.

Our view is aligned with that of Arthur (1999), who does not agree with the epistemological power of Platonic TEs but thinks that TEs can go beyond arguments by offering an effortlessly understandable imaginative reconstruction of the phenomenon. According to Arthur (1999, p. 27), there are no pre-existing concepts but rather some sort of presentiment or intuition of them. This does not mean that such ideas would really exist and that we could not yet understand them. Rather, we have not succeeded in formulating them.

Norton (2004a) has questioned the reliability of the use of those TEs that are supposed to be "the glimpsing a Platonic world". Brown's counterargument is that even ordinary vision can be mistaken (1991, p. 65–66). Norton sees this differently: the TE that fails is simply an argument that contains an erroneous assumption. Brown's Platonism has also been criticised for not presenting criteria for good and poor thought experiments (Brown and Fehige 2010). Brown and Fehige argue that this objection will be weak if the intuitions do the work in thought experiments, since rationalists and empiricists do not have a theory of the validity of intuitions.

Brown's (1991) categorisation of TEs as constructive and destructive has already been used in the analysis of thought experiments in physics textbooks and popular physics books by Velentzas, Halkia, and Skordoulis (2007). When they analysed 25 books to discover how the 11 most essential thought experiments in the domains of relativity and quantum mechanics are presented, they found all of the thought experiments contained in the books to be constructive.

The use of Brown's categorisation shows that it has potential in science education. We believe that it could also be used in science teaching as a theoretical framework of thought experiments for understanding how scientific knowledge is constructed. In the following section, thought experiments are discussed from the perspective of science education.

38.5 Thought Experiments in Science Education

In the course of the past 10 years, there has been a slight increase in research activities related to thought experiments in science education, and thought experiments have received more attention in scientific discussions. Here we argue why and how TEs might be used in science teaching in supporting student learning and offering an authentic image of science. In addition, the possible challenges involved in the teaching and learning of TE will form part of the discussion.

38.5.1 Pedagogical Benefits of Thought Experiments

Ernst Mach was the first to realise that thought experiments might have a high didactical value (Mach 1976). He emphasised in particular the role played by students in thought experimenting (Matthews 1988, 1990). By using thought experiments as a teaching method, a teacher can keep students guessing. In addition, this method provides a significant support to the teacher in coming to know his/her students better. Some students are able to guess the next phase immediately, while some will present extraordinary guesses. Through thought experiments, students will learn to distinguish solvable from unsolvable concerns.

The use of TEs introduces an authentic image of the culture of science (Galili 2009; Reiner et al. 1995; Reiner and Gilbert 2008). TEs can be used to address the essential characteristics of physical theories (Galili 2009). They often employ representative models that eliminate technical details, errors, and impeding factors such as heat or friction. By introducing TEs before real experiments, students may develop an ability to appreciate real experiments and perceive the focus of the experiments, which is otherwise frequently difficult to see because of the sheer quantity of details. Naive observers' difficulties in differentiating between non-relevant and relevant details may impede them from finding out the aimed observations, results, and conclusions (see, e.g. Kozma and Russell 1997; McDermott 1993). Klassen (2006) believes that by devising their own thought experiments, students are mentally engaged in the concepts to be learned, and this, in turn, may help them to construct a deeper understanding of science. Nersessian (1992) claims that "the historical processes provide a model for learning activity itself" and may assist students in constructing representations of scientific theories. Social discussions of TEs may lead students to conceptual refinement and construction of reliable knowledge, as would be the case in science itself (Reiner and Gilbert 2008).

Reiner and Burko (2003) claim that both the TEs devised by physicists and also those formulated independently by students are important in the learning of physics. Scientifically correct TEs constructed by famous physicists enable students to familiarise themselves with the potential of TEs and to see them as a special mode of argumentation. In contrast, incorrect TEs prepare them for the existence of logical and conceptual stumbling stones, the temporary state of knowledge in physics, and the meaning of self- and peer criticism in the construction of physical knowledge. By working on thought experiments independently, students also work through the processes that underlie erroneous reasoning and learn to negotiate over the processes and conclusions with their peers in a relevant form of social interaction (Reiner et al. 1995). Procedures such as these all contribute to the clarification of concepts.

It has also been claimed that the use of TE in teaching stimulates students' interest (Lattery 2001; Velentzas et al. 2007; Velentzas and Halkia 2011) and helps their imaginations to develop (Galili 2009). By introducing situations that are impossible to reproduce despite the sophistication of the available equipment, TEs also become an irreplaceable tool of teaching. According to Galili (2009), this applies especially in the teaching of relativity and quantum physics, where real experiments are not widely used in the classroom, and the use of the multimedia often fails to promote enhanced understanding. Encouragement is also given to the use of thought experiments in teaching if the aim of the teaching is to activate students' cognitive processes with situations that would otherwise be beyond their everyday experiences (Velentzas and Halkia 2010).

38.5.2 The Use of Thought Experiments in Science Textbooks

It has been noted that in some domains of physics such as relativity and quantum mechanics, thought experiments are the main method of presenting the concepts in physics textbooks and popular physics books (Velentzas et al. 2007). Because science teachers often base their teaching on textbooks (Levitt 2002; Yore 1991), textbook studies are an important method for understanding the premises of science teachers' use of thought experiments. In addition, it would appear that studies concerned with teachers' use of TEs are still absent from in the literature.

The extent to which thought experiments are used in science textbooks and the ways in which they have been exploited have been studied by Gilbert and Reiner (2000) and Velentzas, Halkia, and Skordoulis (2007). Gilbert and Reiner's study focused on popular physics textbooks[9] while Velentzas and colleagues looked at both popular science books and physics textbooks.[10]

Gilbert and Reiner (2000) discovered that textbooks often miss opportunities to develop thought experiments suitable for teaching even though there were numerous suitable opportunities to do so. Thought experiments in textbooks frequently turn into thought simulations that lack two essential elements of thought experiments: recognition and approval of the imposed problem and conclusions based on the results. Instead of drawing on the six elements of TEs,[11] the textbook thought simulations typically consisted of the following parts:

i. Statement of the conclusion reached
ii. Creation of the imagined world
iii. Conflation of the design and running elements
iv. Statement of the results obtained, often with an optional restatement of the conclusions reached (Gilbert and Reiner 2000, p. 279)

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[9] The books analysed were Breithaupt's *Understanding Physics for Advanced Level* and Ohanion's *Physics* and *Conceptual Physics* by Hewitt.

[10] The books were either written in Greek or translated into Greek from English. The study aimed at finding out how the books represented the 11 most essential thought experiments in the domains of relativity and quantum mechanics. A total of 25 books were included in the study.

[11] The six elements of a TE: (1) posing a question or a hypothesis, (2) creating an imaginary world, (3) designing the TE, (4) performing the TE mentally, (5) producing an outcome of the TE, and (6) drawing a conclusion.

According to Gilbert and Reiner (2000), this may be the result of the textbook writers not understanding the actual potential of using thought experiments. Indeed, thought experiments can be a successful way to enhance students' cognitive engagement, which is the key to developmental success. Thought experiments offer opportunities for creating new ontological entities, developing reasoning skills, and adopting epistemological engagements. These skills are claimed to be essential for gaining an understanding of physics (Driver et al. 1994). It might also be asked whether this kind of one-sided deductive approach to thought experiments is pedagogically valid.

Velentzas, Halkia, and Skordoulis (2007) observed that all of the thought experiments that they had found in the physics textbooks and popular physics books in their study were constructive. In addition, the authors had modernised numerous thought experiments: for example, Einstein's chest TE was examined in the form of a spaceship thought experiment. The authors had also invented thought experiments independently. The mathematical level of thought experiment was low and the terminology, language, and abstraction level were all modified to match their readers' perceived skills. The use of narratives was typical of the popular textbooks, whereas the other textbooks tended to avoid narratives by using scientific language and terminology.

38.5.3 Studies on the Use of Thought Experiments in Teaching

Thought experiments have been used in science teaching in different ways, and some of the possibilities have been reported. In the following we describe a few of these: using written tasks to help students to understand well-known TEs,[12] constructing historical physics experiments as thought experiments in narrative form (Klassen 2006), and students' own TEs in the context of experimental work (Reiner 1998).

Velentzas, Halkia, and Skordoulis (2007) used the famous TE known as Einstein's elevator thought experiment to introduce the concepts of the equivalence principle to 9th grade students. A group of six students studied the thought experiment as it was presented in a selected popular physics book[13] and replied to related questions, first individually and then as a group. The results indicate that the pupils achieved a reasonable understanding of the concepts. They were also surprisingly enthusiastic about performing the given task. The researchers supposed that this reaction may have been a consequence of the nonmathematical, narrative representation of the task. It seems, then, that popularised thought experiments can be used to inspire pupils in the case of concepts and principles that are discussed in greater depth later in the teaching process.

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[12] See, e.g. Velentzas et al. (2007), Lattery (2001), Velentzas and Halkia (2011), and Velentzas and Halkia (2012).

[13] Stannard, R. (1991). *Black Hole and Uncle Albert*. London: Faber and Faber Ltd.

Velentzas and Halkia (2011, 2012) have also successfully used thought experiments as a teaching tool in physics teaching for upper secondary students. They studied the ways in which the uncertainty principle and the basic concepts of the theory of relativity could be taught to upper secondary school students. The uncertainty principle was introduced via Heisenberg's microscope thought experiment (Velentzas and Halkia 2011), while the theory of relativity was approached via Einstein's train and Einstein's elevator thought experiments (Velentzas and Halkia 2012). In the case of the uncertainty principle, the students were able to derive the uncertainty principle, and by the end of the teaching, they understood it as a general principle in nature (Velentzas and Halkia 2011). Furthermore, Einstein's TEs concerning relativity enabled students to realise situations related to the world beyond their everyday experiences and to gain a basic understanding of the theory of relativity (Velentzas and Halkia 2012).

Lattery (2001) used Galileo's TE Law of Chords (rates of descent along certain curves) as a basis for a student project at the university level. A group of three students discussed the TE and made predictions, following which they tested the predictions experimentally. Subsequently, they wrote a paper, prepared a poster, and made an oral presentation for their peers and the faculty concerned with the project. Lattery concludes that it offered a positive learning experience for the students themselves, for their peers, and for faculty in general.

Klassen (2006) argued that thought experiments could be expressed as stories. To test his hypothesis, he wrote a story about Benjamin Franklin's life and experiments in a form that invited students to render Franklin's experiments as thought experiments. He believed that this kind of narrative construction would help students to become mentally engaged in the concepts to be learned and that this, in turn, would them help to construct a more profound understanding of science. Even if a method of this kind seems to be rather interesting, its effectiveness should still be assessed scientifically by examining students' learning processes before further conclusions.

Reiner (1998) studied grade 11 students' self-devised thought experiments. A total of 12 students were given the following task. Using a computer-based simulator and hands-on equipment, they were required to design a periscope with a wide visual field. To solve the task, the students worked in groups of three. Analysis of the processes produced by one group showed that the students' thought experiments developed because of a collaborative problem-solving process in which the students used the computer system to validate potential events and results. The system helped the students to make their intentions visible to their peers and also to test hypothetical events. Furthermore, the four different student groups displayed a considerable variety of thought experiments, e.g. the logic and contexts that the students used and the conclusions that they drew varied considerably. It was also typical of the four groups that the students' thought experiments were partial and incomplete; they did not contain all three parts of the typical thought experiment: hypothesis, results, and conclusions. Reiner claims, however, that the results show that the thought experiments, which consisted of episodes, were general rather than random, even if they missed out one or two of the three parts. According to Reiner, a collaborative environment helps students to construct thought experiments as a shared construction that is based on individual students' contributions.

These examples of the implementation of thought experiments in teaching are illustrative; but in actual classroom teaching, some limitations may occur. Teachers need to take into account the fact that students' cognitive processes may lead to erroneous conclusions (Velentzas and Halkia 2011). In analysing some of the famous TEs of physics, Reiner and Burko (2003) have discovered cognitive processes that also lead to erroneous conclusions. At least three of this kind were found: strong *intuition* of a kind that induces the abandonment of theory-based reasoning, *incompleteness* of the basic assumption of the thought experiment, and *irrelevance* of the system's properties in the thought experiment.

Reiner and Burko (2003) claim that the processes that are characteristic of physical thinking are likely to be found in physics learning as well. The use of intuition instead of logical, theory-based reasoning is even stronger in the case of naive physics learners than amongst famous physicists in the history of physics. In addition, research has shown that students more often apply concrete, experiential knowledge rather than using logical reasoning (e.g. DiSessa 1993; Gilbert and Reiner 2000). The incompleteness of the students' TEs relates to the narrowness of the learners' physical world. Their readiness to conclude is insufficient because assumptions integrated into knowledge structures are partial instead of being comprehensive; the learners may not have sufficient knowledge of the physical world to make sense of the TE. Reiner and Burko (2003) argue that the use of TEs in physics learning is important, because it allows students to experience the destructive and constructive role of physical intuitions, incompleteness, and the importance of relevancy.

We agree with Reiner and Burko and Velentzas and Halkia (2011), who recommend the use of TEs in cases where the performance of a physical experiment is impossible, harmful, and dangerous or has nothing to offer in the end for the result. They also suggest the use of TEs in situations that require students to mentally surpass their everyday experiences.

In sum, thought experiments can be used in science teaching to help students to develop their conceptual understanding of science.[14] Thought experiments may increase students' interest in learning science[15] and to activate and support their thinking processes.[16] In addition, the construction of students' own thought experiments can be supported by creating a collaborative environment that enables students to construct thought experiment together with their peers (Reiner 1998). Students' erroneous conclusions should, however, be taken into account in teaching; they can be used as a basis for discussion about the destructive and constructive intuitions in thought experimenting (Reiner and Burko 2003).

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[14] See Galili (2009), Velentzas et al. (2007), and Velentzas and Halkia (2011, 2012).

[15] See, e.g. Gilbert and Reiner (2000), Velentzas et al. (2007), and Lattery (2001).

[16] See, e.g. Reiner and Burko (2003), Reiner and Gilbert (2008), and Velentzas and Halkia (2011, 2012).

38.6 Conclusion

This article has examined the role played by thought experiments in science and science education. It has been argued that TEs are a natural part of scientific methodology, a special type of scientific experimentation that may play either a constructive or a destructive role in the construction of scientific theories. The important role played by TEs in science should also be discussed in science teaching. In addition, TEs have been used in science education in various ways to foster the development of students' reasoning, mental modelling, and conceptual understanding; to teach them about the nature and processes of science; and to stimulate their interest in science. Thought experiments also provide opportunities for focusing on the epistemology and ontology of science in the teaching of science.

TEs are a special variety of scientific experiment that can, at its best, precede a physical experiment and help the experimenter in conducting it. In some cases, physical experimentation may not yet be possible and the TE can be the only way to experiment; TEs are free from the constraints imposed by the learning environment and by technical restrictions (Cooper 2005; Galili 2009). In addition, a physical experiment may be considered useless if it is unlikely to substantially improve understanding gained from a TE (Sorensen 1992). These statements also hold true in science education: TEs can be used as an effective tool for teaching. By performing a TE before the physical experiment per se, students may develop their ability to see the focus of the physical experiment (Galili 2009). At times, the experiment can only be made mentally as a TE for practical reasons: the school may not have certain equipment or the experiment is too laborious to be conducted during a lesson. In some cases, thought experimenting is the only way to experiment because the situation cannot be performed as a physical experiment, regardless of the sophistication of the equipment available (Galili 2009). TEs also frequently involve idealisations such as technical details, errors, and impeding factors such as heat or friction; these factors can be eliminated by using TEs (Cooper 2005; Galili 2009). This particular use of TEs in school teaching may already be more common than might be expected.

TEs in science can be fallible, but the mistakes can also teach important lessons that help scientists to develop scientific theories. For instance, erroneous conclusions in famous TEs can be explained in terms of three different cognitive processes: strong *intuition*, which induces the abandonment of theory-based reasoning; the *incompleteness* of the basic assumptions of thought experiment; and the *irrelevance* of the properties of the system in the thought experiment (Reiner and Burko 2003). This kind of erroneous reasoning is also likely in the case of students; teachers should also be prepared to take it into account in their teaching (Velentzas and Halkia 2011). Teachers should also be prepared to encourage students to experiment mentally. As Ozdemir's (2009) results have shown, even physics graduates may tend to think that mental simulations cannot be used correctly to explain the phenomena of physics. Hence, teachers should be ready to help their students to become more open-minded and to be undaunted by errors in their reasoning. Teachers need to help their students to gain an insight into the value of thought experiments in scientific reasoning since they may otherwise remain unaware of it (Reiner 2006).

Thought experiments can be used in science teaching to allow students to see that scientific intuitions can play both destructive and constructive roles. It has, however, been observed that authors of science textbooks and popular science books may be in the habit of using only constructive TEs (Velentzas et al. 2007). This rather one-sided use of TEs may bias the image of science that the books attempt to convey. If the authors of textbooks aim at conveying an image of the processes of science, then the use of TEs in textbooks should be carefully designed to include both destructive and constructive TEs.

It must also be emphasised that, when conceptually demanding thought experiments have been simplified for teaching a particular student group, it has been noted that thought experiments stimulate the students' interest (Velentzas et al. 2007). Our own approach tends to agree with that of other researchers who acknowledge that this use of TEs works well if the concepts are taught in greater detail at a later stage. Reconstruction of historical physical experiments as thought experiments has also been reported to enhance students' interest (Klassen 2006).

The role played by a skilful teacher is pivotal in the use of thought experiments in science teaching. Students' own thought experimenting needs to be supported by the teacher by means of the selection of suitable resources, the structuring of the learning activities, and guidance of the students' experimentation (Hennessy et al. 2007). A skilful teacher is able to observe instances of erroneous reasoning and knows how to guide students' learning processes in the right direction. To be able to evaluate thought experiments in science textbooks and also thought experiments implemented by students, a teacher should present or formulate the theoretical background and criteria for the elements of a TE. Gilbert and Reiner (2000, p. 268) provide a system of categorisation for thought experiments that appears to be promising for understanding the use of TEs in science teaching. The categorisation is briefly as follows. An *expressed thought experiment* is a TE that has been placed in the public domain by an individual or a group of researchers. A *consensus thought experiment* is a TE accepted by at least some of the scientific community and one that has been scientifically justified, that is, published in a scientific journal.

In addition, a *historical thought experiment* is a TE that has already been replaced in science but may still be used to explain particular phenomena economically. A *teaching thought experiment* contains "the criterion by the teacher (or, indeed, the taught) of the TE based on the situations familiar to or imaginable by the students, through which to develop an understanding of a given consensus TE". Gilbert and Reiner emphasise that all of the different types of TEs include the six elements of TEs described by Reiner (1998).

As Gilbert and Reiner (2000) point out, although different types of thought experiment exist in science, they all have a certain structure. Hence, thought experiments devised and conducted by students should also include these common elements in order to qualify as genuine thought experiments; if some of the elements are missing, then the exercise should be termed a thought simulation rather than a thought experiment (Gilbert and Reiner 2000). According to some studies, historical TEs have sometimes been modernised in textbooks to be more readily understandable (see, e.g. Velentzas et al. 2007). This reconstruction may, however, lead to another problem: textbooks do not always include all of the necessary elements of thought experiments, with the result that TEs that have been reduced as thought simulations will lead to loss of the necessary cognitive engagement (Gilbert and Reiner 2000). Such thought simulations may nevertheless be used to some extent in science teaching if the primary goal of the teaching is not the actual subject matter or to foster students' understanding of the processes of science but rather to stimulate the students' interest in the science per se. Naturally, it would be unreasonable to assume that, for instance, secondary students would be able to perform thought experiments as effectively as, say, university students. It is perhaps self-evident that the science teacher should have the freedom to decide just how accurate students' mentally performed experiments need to be for them to fulfil the criteria of a thought experiment.

Undoubtedly, TEs need to be considered carefully in the context of science teacher education, and in-service education would need to be organised for practicing teachers. Both pedagogical and subject-matter departments could introduce TEs to students as part of the history and philosophy of science teaching. In addition, many subject-matter courses, such as mechanics, thermodynamics, and quantum physics, offer good opportunities for the use of TEs in the teaching of subject matter. In this way, TEs could become better integrated into the knowledge structures of future science teachers, who could then use thought experiments flexibly in their own science teaching. As Matthews (1992, p. 28) suggests, "A historically and philosophically literate science teacher can assist students to grasp just how science captures, and does not capture, the real, subjective, lived world".

Systematic research into the use of TEs in science teaching is, however, definitely needed so that we can acquire further research-based, valid information on their effective use at various educational levels. In particular, the notion of a *teaching thought experiment* is interesting from the perspective of science teaching as conducted in schools. It would be interesting to discover the kind of TEs that teachers use and how they use them, and whether teachers use thought simulations (TSs) rather than TEs. It is likely that consensus and historical TEs are not widely used in teaching at secondary school level, but teaching TEs may nevertheless prove to be more common than is thought. Thus far, the groups participating in the studies have been small and they have varied from lower secondary school pupils to university students. In consequence, the results cannot be readily compared; and hence our recommendations for the use of TEs in teaching are inevitably still rather loosely based. Nevertheless, analysis of students' thought experiments has interesting possibilities that may help us to understand better the challenges posed by science learning. There is undoubtedly a need for further studies of how science teachers actually use TEs in their teaching. This gap in the literature deserves to be filled.

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Part X

Theoretical Studies: Teaching, Learning and Understanding Science

Chapter 39
Philosophy of Education and Science Education: A Vital but Underdeveloped Relationship

Roland M. Schulz

> *It was through the feeling of wonder that men now and at first began to philosophize. … but he who asks and wonders expresses his ignorance … thus in order to gain knowledge they turned to philosophy.*
>
> —Aristotle *(Metaphysics)*

39.1 Introduction

This chapter examines the relationship between the two fields of science education and philosophy of education to inquire about how philosophy could better contribute to improving science curriculum, teaching, and learning, above all teacher education. The value of philosophy *for* science education in general remains underappreciated at both pedagogical levels, whether the research field or classroom practice. While it can be admitted that philosophy has been an area of limited and scattered interest for researchers for some time, it can be considered a truism that modern science teacher education has tended overall to bypass philosophy and philosophy of education for studies in psychology and cognitive science, especially their theories of learning and development (which continue to dominate the research field; Lee et al. 2009). A major turn encompassing philosophy would thus represent an *alternative approach* (Roberts and Russell 1975).

Science education is known to have borrowed ideas from pedagogues and philosophers in the past (e.g., from Rousseau, Pestalozzi, Herbart, and Dewey; DeBoer 1991); however, the subfield of *philosophy of education* has been little canvassed and remains on the whole an underdeveloped area. At first glance such a state of affairs may not seem all too surprising since science education is mainly concerned

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with educating students about particular science subjects or disciplines. But this necessarily implies a tight link between content and education. Hence, if education is to mean more than mere instructional techniques with associated texts to encompass broader aims including ideals about what constitutes an educated citizen (i.e., defining "scientific literacy") or foundational questions about the nature of education, learning, knowledge, or science, then philosophy *must* come into view (Nola and Irzik 2005). As is known, an *education in* science can be, and has been, associated with narrow technical training, or with wider liberal education, or with social relevance (STSE), or lately with "science for engineers" (US STEM reforms), an updated version of the older vocational interest.[1] Yet all these diverse curricular directions imply or assume a particular educational philosophy which is rarely clearly articulated (Matthews 1994a/2014; Roberts 1988; Schulz 2009a).

At second glance then, and viewing science education in a broader light, being principally at home in education unavoidably implies an excursion into philosophy of education. In fact, it avoids this subfield of philosophy at its own peril, as argued elsewhere (Matthews 2002; Schulz 2009a, b). Equally, there are lessons to be learned from its own past, yet most science teachers and too many researchers seem little aware, or even concerned to know, about the rich educational philo-historical background of science education as it has developed to the present, whether in North America, Europe, or elsewhere (some examples are Mach, Dewey, Westaway, and Schwab; DeBoer 1991; Gilead 2011; Matthews 1990b). In fact recent critical reviews insist educators must acknowledge and respond to how past historical developments have molded science education while continuing to adversely shape the current institutionalization of school science (Jenkins 2007; Rudolph 2002). A central concern of this chapter is to emphasize the value of philosophy in general and philosophy of education in particular. It will be claimed an awareness of the worth of these fields can have positive results for further defining the *identity* of both the science teacher as professional (Van Driel and Abell 2010; Clough et al. 2009) and science education as a research field (Fensham 2004). The perspective to be taken on board is that to teach science is to have a philosophical frame of mind—about the subject, about education, and about one's identity.

39.2 Philosophy of Science Education Framework

To be clear from the start, there is no attempt made here at formulating a particular philosophical position thought appropriate for science education, in contrast to such discussions having taken place in mathematics education for some time. In that field

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[1] The prominent US *National Science Teachers Association* (NSTA) has made STEM a central reform emphasis: www.nsta.org/stem. References for the other more common science classroom curricular emphases are Aikenhead (1997, 2002, 2007), Carson (1998), DeBoer (1991), Donnelly (2001, 2004, 2006), Pedretti and Nazir (2011), Roberts (1982), Schwab (1978), Witz (2000), and Yager (1996).

several educators have articulated and debated the notion of a "philosophy of mathematics education," for example, Platonism and foundationalism versus social constructivism and fallibilism (Ernest 1991; Rowlands et al. 2011). On the other hand, it will be stressed that the development of a "philosophy *of* science education," that is, an "in-house philosophy" for the field, could be significant for reforming science education. It can be acknowledged that math educators have been in the forefront of attempting to establish a "philosophy of" for their educational discipline, while science educators in the main have not yet come to consider or value such an overt evolution in their field. Such an endeavor urges exploration of new intellectual territory.

The sign of the times seems ripe for such an investigation ever since the science educational field became staked out by opposing, even irreconcilable positions "from positivism to postmodernism" (Loving 1997).

In the past constructivism was once seen by many educators as a kind of "philosophy" (though not expressed as such) which was to serve the role as a "new paradigm" of science education. Today, however, this view is considered mistaken, although the topic is divisive (Matthews 2002; Phillips 1997, 2000; Suchting 1992).[2] This judgment has come about largely because many supporters at the time did not reflect seriously enough about the philosophical underpinning of its various forms—cognitive, metaphysical, and epistemological.[3] Constructivism remains a dominant and controversial topic in education, but one lesson to be had from the heated debate of the past three decades is that absence of philosophical training among science educators became apparent (Matthews 2009b; Nola and Irzik 2005). Another lesson learned is the absence of any explicit discussion regarding educational philosophy, even though constructivism in some corners was brashly substituted for one. In hindsight it surprises that constructivism—which after all still finds its principal value as learning theory (and perhaps teaching method)—could be mistaken as a dominant kind of "philosophy of" science education at the neglect of broader aims and concerns relevant to educational philosophy, as to what it *means* to educate someone in the sciences. And science education once again showed unawareness of its own history, since Dewey (1916, 1938, 1945) and Schwab (1978) had previously addressed such concerns. At minimum the case of constructivism had illustrated—although not widely recognized—how interwoven, if not dependent, science education in the academy had become with certain psychological ideas and philosophy of science (notably its Kuhnian version; Matthews 2003a).

In light of this background, it will be of some interest to teachers and researchers to raise anew the question of developing a "philosophy of" science education (PSE),

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[2] "Regrettably, much of the constructivist literature relating to education has lacked precision in the use of language and thereby too readily confused theories of knowledge with ideas about how students learn and should be taught" (Jenkins 2009, p. 75).

[3] The literature on constructivism is vast. Critiques are found in Davson-Galle (1999), Phillips (2000), Grandy (2009), Kelly (1997), Matthews (1998b, 2000), and Scerri (2003). Also see chapter 31 in Handbook.

by asking here what that could *mean* and could *offer* the discipline. The intent is to address these concerns and help sketch out contours. With this project in mind, one can draw attention to two useful aspects pertaining to philosophy in general which can come to our aid and contribute to improving science education and developing such a philosophical perspective: the ability of philosophy to provide a synthesis of ideas taken from associated disciplines with their major educational implications and providing what can be called “philosophies of.” In this way it will be shown how philosophical thought can be brought to bear directly on educational ideas and practice.

39.2.1 The Synoptic Framework

The role and value that philosophy itself and its two important subdisciplines of *philosophy of science* (PS) and *philosophy of education* (PE) can have is illustrated by the representation below. Note that “philosophy of science education” (PSE) can then be understood as the *intersection* or *synthesis* of (at least) three academic fields. For each respective field of study, some individual points are stressed which comprise core topics of interest to science education pertinent to each, but is meant to be illustrative not exhaustive:

The framework in itself assumes neither prior philosophical positions (e.g., metaphysical realism or epistemological relativism) nor pedagogical approaches (e.g., constructivism, multiculturalism, sociopolitical activism). As a graphic organizer it does provide science teachers and researchers a holistic framework to undertake analysis of individual topics and perhaps help clarify their own thinking, bias, and positioning with respect to different approaches and ideas. The main point is to show that any particular PSE as it develops for the teacher or researcher should take into consideration, and deliberate upon, the discourses pertinent to the three other academic fields when they impinge upon key topics in science education. At minimum it should contribute to helping develop a philosophic mind-set.

In sum (as Fig. 39.1 shows), any philosophy of science education (PSE) is foremost a *philosophy* (“P”) and as such receives its merit from whatever value is assigned to philosophy as a discipline of critical inquiry. (This value may not appear at all obvious to science educators.) Furthermore, such a philosophy would need to consider issues and developments in the philosophy, history, and sociology of science (“PS”)[4] and analyze them for their appropriateness for improving learning *of* and *about* science. Finally, such a philosophy would need to consider issues and developments in the philosophy of education and curriculum theory (“PE”) and analyze them for their appropriateness for education in science, as to what that can *mean* and how it could be conceived and best achieved. A fully developed or

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[4] This component is meant to include the associated disciplines and not just the philosophy discipline itself.

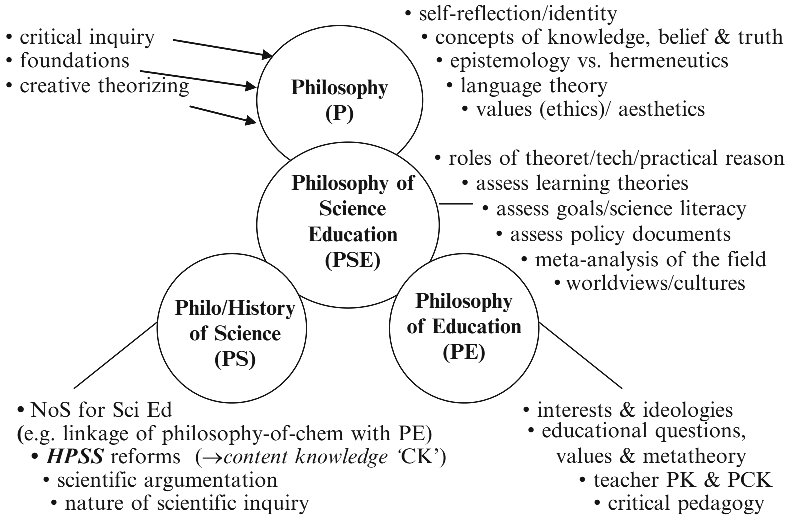

Fig. 39.1 Philosophy of science education (PSE)

"mature" PSE can be understood as an integration of all three fields. It ultimately aims at improving science education as a research field as well as assisting teachers in broadening their theoretical frameworks and enhancing their practice.

39.2.2 *Providing "Philosophies of"*

Philosophy today has evolved into several specialized subdisciplines. These include philosophy of science, of education, of mathematics, of technology, of history, of religion, and others, which can collectively be called "philosophies of." It is especially the first two that are of immediate concern to us when developing one for ourselves, as Fig. 39.1 illustrates. And yet this conceptualization is not as new as it may appear. Over 40 years ago, the philosopher Israel Scheffler summarized the value of these "philosophies of" for science educators:

> I have outlined four main efforts through which philosophies-of might contribute to education: (1) the analytical description of forms of thought represented by teaching subjects; (2) the evaluation and criticism of such forms of thought, (3) the analysis of specific materials so as to systematize and exhibit them as exemplifications of forms of thought; and (4) the interpretation of particular exemplifications in terms accessible to the novice. (Scheffler 1970, p. 392)

He understood these "philosophies of" would provide invaluable components to a science teacher's identity and preparation, in addition to the common three of (i) subject matter competence, (ii) practice in teaching, and (iii) educational methodology. Especially the inclusion of philosophy of science (PS) topics he considered vital to allow teachers to be "challenged to reflect deeply on the foundations" of their subjects and "to relate their reflections to the task of teaching" (p.388).

Matthews (1994a, b, 1997) is known to have helped popularize Scheffler's earlier vision, whose call for inclusion of PS has been broadly acknowledged today though unfortunately little implemented worldwide in teacher education programs.[5] He has expanded upon Scheffler's line of reasoning to include additional pedagogical and professional arguments. An improved pedagogy, for example, should include several aspects: wisely evaluating constructivism and the educational aims of curricular documents, integrating HPSS topics, developing critical thinking, allowing science courses to show a "human face," and at minimum making science more interesting and understandable. Enhancing professionalism requires teachers to develop a wider perspective of their subject and its role in education, including becoming versed with topics and questions associated with science and society concerns. These would include religion and science, "multicultural science," feminism, techno-science, environmental ethics, animal rights, and others.

In short, philosophical questions concerning both education and science are at the heart of the science education profession, many of which have kept, and continue to keep, teachers, researchers, and curriculum developers engaged. Broadly speaking, they encompass essential concerns immediately identifiable with the two fields of philosophy of education (PE) and philosophy of science (PS):

> … educational ones about the place of science in the curriculum, and how learning science contributes to the ideal of an educated citizen and the promotion of a modern and mature society. The questions also cover the subject matter of science itself. What is the nature of science? What is the status of its knowledge claims? Does it presuppose any particular worldview? The first category of questions constitutes standard philosophy of education (PE); the second category constitutes philosophy of science (PS) or history and philosophy of science (HPS). (Matthews 2002, p. 342)

The teacher's professional role today has in some cases also come to include cocreating, advising, and assessing so-called national science "standards" documents. Since the 1990s several countries around the world have sought to define curriculum "standards," which harbor considerable agreement on nature-of-science policy statements (McComas and Olson 1998). "Clearly all these curricular exhortations depend on teachers having philosophical acumen and knowledge in order to understand, appraise, and enact them. This requires a mixture of philosophy of science (to understand the substantial claims), and philosophy of education (to interpret and embrace the objectives of the curricula)" (Matthews 2002, p. 343). The same arguments and considerations apply to mathematics education where philosophy *of* mathematics is integral to what, why, and how mathematics is taught and assessed and how teachers understand their professional role and responsibilities.

In the sections below, the intention is to further elaborate on the worth of philosophy as a subject in general, but especially philosophy of education since

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[5] Whether or not science students themselves should be presented with PS ideas and controversies is still being debated among researchers (Hodson 2009). One philosopher of education has reversed his earlier standpoint (Davson-Galle 1994, 2004, 2008a).

this topic is usually overlooked. Philosophy of science for educators will only be glossed (above all its newer subspecialties) as this topic has been an active area of research.

39.3 The Value of Philosophy

Philosophy is an academic discipline that seeks to establish a systematic reflection on reality however it may be construed. Its analytic function, often termed rational inquiry, involves critical appraisal of different topics, beliefs, and schools of thought.[6] Because of the complexity of the world around us (both natural and artificial), philosophy has been traditionally divided into separate major fields of study (first accredited to Aristotle) such as metaphysics, epistemology, logic, ethics, aesthetics, and politics. These fields individually have either major or lesser bearing on science education directly. The *first two* have played a significant historical role pertaining to our understanding of the nature of reality, of knowledge, and of science:[7]

- ***Ontology***: the branch of philosophy (metaphysics) that concerns itself with the most general questions of the nature or structure of reality: what "is" or "what is *being*?" and existence. It examines natural and supernatural claims and asks about the feature of essences (e.g., are natural kinds, like species, universal or nominal?). Questions regarding *scientific* ontology are concerned with ascertaining the status (or validity) of the products of human creativity or discovery; included are scientific models and theoretical entities (e.g., gene, field, black hole, tectonic plates), evaluated as to their truth (realism) or merely useful (fictive) construct to solve problems and "fit" experimental data (empirical adequacy).
- ***Epistemology***: the branch of philosophy that studies the nature of knowledge, its scope, foundations, and validity; it deals with theories of knowledge, distinctions between believing and knowing, and justification. *Scientific* epistemology is concerned with describing and ascertaining the nature of both the body of known scientific facts and theories (degree of certainty) *and* the production of new knowledge (i.e., scientific inquiry). *Personal* epistemologies are commonly taken to include individual beliefs, views, and attitudes about a particular subject; hence, they can be considered a "personal knowledge framework"

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[6] It has also been historically associated with particular schools of thought (e.g., idealism, rationalism, empiricism, existentialism); hence, particular *philosophies* which themselves are often associated with individual philosophers (e.g., Plato, Kant, Marx, Nietzsche).

[7] This is not meant to discount the next three. Logic has made a renewed appearance in science education under the guise of critical thinking and scientific argumentation; those in ethics intersect with discussions of values and socio-ethical issues (Allchin 2001; Corrigan et al. 2007; Witz 1996; Zeidler and Sadler 2008); even aesthetics has been considered for the field (Girod 2007).

(i.e., "what do you know about 'X', and how do you know (it)?"). Two competing views of epistemic justification are *foundationalism* and *coherentism*.[8]

As mentioned, the significance of *philosophy of science* for science education is generally recognized today—though moreso among researchers than science teachers themselves (Duschl 1994, 1988; Hodson 2008; Matthews 1994a)—while philosophy per se is accorded much lesser importance, notwithstanding the limited forays by some researchers into its subfields, which can be acknowledged (e.g., language studies, post-structuralism, hermeneutics, scientific argumentation, "critical theory"). Why this situation has arisen and persists is an open question and would require its own socio-empirical research, and hence is not of immediate concern of this review. But it remains an important question that should be pursued as it could reveal much about our community, about how science education is perceived and undertaken. In other words, it aims at the core of the self-understanding of science education as profession and identity (Fensham 2004).

A familiar question posed by preservice and science teachers alike is: "What does philosophy have to do with science?" or more succinctly and less pejoratively "how can any sort of 'philosophy' contribute to helping my students better understand difficult *scientific* concepts?" Such questions implicitly assume of course a deep divide between science and philosophy, certainly between science education and philosophy.[9] While science teachers need not be openly hostile to philosophy, they certainly appear indifferent. Much responsibility can be laid at the door of the academy, its structure, culture, and teacher training. Their attitudes and preparation effectively expose much about how teacher identity is formed,[10] about preconceptions of knowledge, but also about the nature of university science education and scientific specialization, including the nature and influence of science textbooks.[11]

Classroom teachers tend to be more concerned with valuable but mundane matters of decision-making regarding immediate instruction, learning, and assessment. For them as pertains their professional duties and identity, these concerns have little if anything to do with philosophy—or so it would seem. A consequence of this disregard makes providing educational rationales of their thinking and practice a

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[8] See the chapters in Bonjour and Sosa (2003) for a concise overview; Sect. 39.5.2.2 targets the former.

[9] That one must inevitably justify the value of philosophy for teachers and many researchers suggests a cultural predicament already exists concerning what constitutes "education" in our present age.

[10] Which includes essentially their "orientations" towards teaching, identified in science teacher education research as formative dispositions attached to identity (Van Driel and Abell 2010; Witz and Lee 2009)

[11] Probably the ongoing reality of the academic divide between the "two cultures" maintained as two solitudes in universities to this day (as described by C.P. Snow; Shamos 1995; Stinner 1989) contributes to the hostility or indifference since science teachers are not generally required to endure Arts faculty courses. All this in combination with the common negative *image* that academic philosophy is preoccupied with obtuse speculation, arcane technical jargon, and unresolved disputes are remote from everyday matters. Certainly quite different, encouraging evaluations can be had (Matthews 1994a; Nola and Irzik 2005).

challenge: "When planning lessons, teachers often struggle when asked to express how they decide what science content within a discipline is worth teaching. Rationales are post-hoc and rarely reflect deep thinking about the structure of the discipline, or how students learn …" (Clough et al. 2009, p. 833).[12] Their struggles become quite apparent when further asked to give an explicit account of their "philosophy of teaching" or "philosophy of learning." And this counts not just for content teaching and conceptions of learning but equally for providing truly *educational* objectives for either their individual courses or overall science education.[13] Seldom are the contextual aspects of teaching the subject matter made explicit even though *seven* competing "curriculum emphases" have been identified in science educational history (Roberts 1988). In effect, particular curricular emphases bear witness to buried educational philosophies. The teaching profession itself is mired in a scenario of what Roberts (2007) has astutely identified as two substantial conflicting "visions" of science education.[14] These facts alone warrant developing philosophical acumen for teachers.

If this picture as sketched is indicative of teacher training and science education culture, then emphasizing the significance of philosophy, especially philosophy of education, would require a "paradigm shift" in thinking. Exactly this sort of thing had been recommended by Jenkins (2000) for effective reform of that culture, although the present proposal would encompass a wider scope than was initially suggested.[15]

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[12] They continue: "… Too often the selected textbook defines course scope, sequence, and depth implying that a textbook's inclusion of information, in part, legitimizes teaching that content. Textbooks also exert a significant influence on *how* content is taught…" (ibid).

[13] Many teachers would probably declare "science for all" or "scientific literacy" though seldom with awareness these slogans are replete with ambiguities—the latter goal even suffering inherent incompatibilities due to serious shifts in connotation, and this despite its ultimate prominence in worldwide "standards" documents (Jenkins 2009; Schulz 2009b; Shamos 1995). The science for all theme arguably partially appropriate for junior science nonetheless vanishes when specialty upper secondary or tertiary courses are reached, for here the status quo is maintained as "technical pre-professional training" (Aikenhead 1997, 2002, 2007). In this case an extreme narrowing of the "literacy" notion is found, HPSS aspects are distorted or abused, while the concealment of existent curriculum ideologies remains unrecognized in absence of educational philosophy (e.g., scientism, academic rationalism, "curriculum as technology" or social utility; Eisner 1992).

[14] In his comprehensive review, the categories "vision I" and "vision II" were postulated to account for two major competing images of science literacy behind many curricular reforms. The former designates those conceptions which are "internally oriented," that is, towards science as a knowledge- and inquiry-based discipline and including the image of science education as heavily influenced by the identity, demands, and conceptions of the profession. The latter vision, alternatively, is "outward looking," towards the application, limitation, and critical appraisal of science in society—the image influenced instead by the needs of society and the majority of students not headed for professional science-based careers. Here the question of the "social relevance" of the curriculum is paramount. He claims that while the second vision can encompass the first, the opposite is not true.

[15] For linked views, see Anderson (1992), Fensham (2004), Matthews (1994a/2014, 2002), and Schulz (2009a).

Philosophy in truth cannot be avoided, and not just for analyzing national "standards" documents, providing coherent rationales or detecting curricular ideologies. Science teachers inadvertently find themselves in its territory when confronted by diverse events, such as (i) explaining common scientific *terms* (like "law," "theory," "proof," "explanation," "observation"), or (ii) student-driven *quandaries* ("how do we know X?"; "do models reflect reality?"; "why are we studying this?", etc.), or (iii) when teacher and pupil together come across science-related public *controversies* (e.g., climate change, nuclear weapons, evolution versus intelligent design)—never mind popular beliefs and media reports (e.g., astrology or alien abductions). Such occurrences usually illustrate that "philosophy is not far below the surface" in any classroom (Matthews 1994a, p. 87). Moreover, the scientific tradition (as an integral part of Enlightenment culture) based on rationality, objectivity, and skepticism, which teachers have inherited, is equally challenged by strands of pseudoscience, irrationality, and credulity of the times (Hodson 2009; Slezak and Good 2011). How can teachers illustrate these differences, especially the distinction between valid and reliable knowledge claims from invalid ones (or natural from supernatural claims), without philosophical preparation? Yet it is not just the classroom, contemporary media discourse, or pop culture that is infused with questions, beliefs, claims, and counterclaims of philosophical significance, but likewise the evolution of science itself.

When science is seen historically, its development has always been interwoven with philosophical interests and debates, whether concerning epistemology, logic, metaphysics, or ethics (the major subfields of philosophy proper). A quick survey makes this evident: from debates on the nature of matter or motion in Ancient Greece to questions of logic, method, and truth with Galileo and Kepler during the Copernican revolution (or Descartes and Newton in the Enlightenment), also Lyell and Darwin concerning the age of the Earth or origin of species, respectively, in the nineteenth century (which saw the realist controversy about atoms in chemistry revived). Right down to our present age, philosophical controversies exist whether concerning the onto-epistemological debates in quantum mechanics or reduction in chemistry.[16]

The history of science, furthermore, is not simply a survey of fantastic discoveries, ideas, and theories as too many textbooks would imply, but is equally littered with discarded concepts and discredited theories (e.g., ether, epicycles, phlogiston, phrenology, caloric, Lamarck, Lysenkoism). Can teachers distinguish between quasi-histories and pseudo-histories or unmask how subject matter is organized to reflect the typical linear, non-controversial, and progressive accumulation of scientific knowledge, imitating the myth of "convergent realism?" (Kuhn 1970, 2000; Laudan 1981). The textbook's and one's personal view of scientific knowledge and

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[16] It should not be forgotten that the seventeenth-century scientific revolution introduced "science" as a field of research and study under the academic umbrella of *Natural Philosophy* to distinguish it from the reigning scholasticism of the universities, hermeticism, and Neoplatonism. Our modern conception of the term and the severance of philosophy from science are of relatively recent origin. The division emerged historically as a development in intellectual thought and specialization, which evolved within European industrial society in the mid-nineteenth century.

its development both presume prior philosophical commitments (e.g., positivism? empiricism? naïve realism? critical realism? social constructivism?) (Duschl 1988; Säther 2003; Selley 1989; Smolicz and Nunan 1975).

Regarding ethics, one should not forget that Socrates was condemned on moral and religious grounds—as were Bruno, Galileo, and Darwin (though not exclusively). Eugenics, once the scientific "hard core" of the social Darwinism movement, was considered a legitimate topic of scientific research less than a century ago. Even modern physics cannot escape this subject, ever since Oppenheimer made the self-incriminating remark that physicists "had known sin" by developing the atomic bomb. The American philosopher C.S. Pierce had stated: "Find a scientific man who proposes to get along without any metaphysics . . . and you have found one whose doctrines are thoroughly vitiated by the crude and uncriticised metaphysics with which they are packed."[17] Studies in history, philosophy, and sociology of the sciences (HPSS) have made this claim abundantly apparent. These fields cannot be either ignored or glossed during science teacher education, but require time and attention for the emergence of an adequate PSE.

We have already noted the worth of philosophy (along with key aspects mentioned above) to lie in providing teachers with both (i) the perspective for synthesis of their educational enterprise by developing a PSE framework and (ii) making available to them in-depth studies termed "philosophies of." Linked to the latter, coming again to philosophy of science (appearing as the "PS" corner of the Fig. 39.1 triangle), teachers need to be made aware that in the past 20 years, new avenues of scholarship have been developing *within* the subfield itself to help them expand their foundational understanding of their specialty (e.g., philosophy of chemistry, philosophy of biology).[18] Here questions concerning major issues in subject matter content that bear directly on senior courses are being discussed. For example, there is dissention whether laws and explanations in biology and chemistry are of the same order and function as those in physics—normally taken for granted in PS literature.[19] Such "cutting-edge" philosophical research has acute ramifications for secondary and postsecondary education, expressly *subject epistemology*, including nature-of-science discourse (Irzik and Nola 2011; Jenkins 2009; Matthews 1998a).[20]

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[17] Quoted in Matthews (1994a), p. 84.

[18] Scientists and philosophers alike have found it necessary to launch important new *subdisciplines* to address foundational questions and concerns arising from their scientific areas of expertise—notwithstanding those scientists who disparage the study of PS overall (e.g., Weinberg 1992). Philosophy of physics (Cushing 1998; Lange 2002), philosophy of chemistry (McIntyre 2007; Scerri 2001), and philosophy of biology (Ayala and Arp 2009) are becoming established research fields, including philosophy of technology (Scharff 2002), likewise lauded for teachers today (De Vries 2005).

[19] Refer to the respective chapter in this Handbook.

[20] Unfortunately it appears that science education worldwide and many science teachers themselves have tended not to keep abreast of these advances and what they possibly offer for curriculum design, instruction, and reform efforts. One might hope these subdisciplines offer, minimally, deeper and improved insights about subject content but, moreso, a better understanding of the essence of the discipline, the core of which teachers are required to inspire and impart to their

In addition to the above mentioned reasons, the worth of philosophy plainly lies in self-reflection. This means nothing less than to reassess one's own practice, educational ideas and aims; even going so far as to reevaluate one's own constructed sociocultural science teacher *identity*. Along with suggesting "philosophies of," Scheffler also argued that science teachers require philosophy as a "second-order" reflective capacity into the nature of their work, their understanding of science, and their educational endeavors. He considered this capacity analogous to the role philosophy of science plays when examining science:

> The teacher requires … a general conceptual grasp of science and a capacity to formulate and explain its workings to the outsider … No matter what additional resources the teacher may draw on, he needs at least to assume the standpoint of philosophy in performing his work … Unlike the researcher [or the academic] he cannot isolate himself within the protective walls of some scientific specialty; he functions willy-nilly as a philosopher in critical aspects of his role. (Scheffler 1970, p. 389)[21]

These proposals of Scheffler can equally be associated today with requirements to enhance teachers' "pedagogical content knowledge" (PCK: Abell 2007; Van Driel et al. 1998; Shulman 1987), which not only means developing *their epistemology* of science (Matthews 1994a/2014, 1997) but in addition their familiarity with philosophy of education topics (Matthews 2002; Schulz 2009a; Waks 2008). Again, Fig. 39.1 displaying the philosophy of science education (PSE) framework identifies these important aspects and illustrates how they are related to, and embedded within, the three corresponding dimensions of P, PS, and PE.

Philosophy in a nutshell then corresponds to the ancient Socratic dictum to examine oneself, and that "the unexamined life is not worth living." Transposing this motto, "the unexamined pedagogy is not worth doing"; in fact it is unsuccessful (as conceptual change research has uncovered)—if not harmful (i.e., indoctrination into scientism[22]).

Such an examination aligns with Kant's famous definition of Enlightenment as the emergence from one's self-imposed immaturity (due to reliance upon

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students. Certainly these are less well known to science teachers and not canvassed by science education researchers to the extent of interest shown in the post-structuralist and "science studies" literature. See Allchin (2004), Collins (2007), Hodson (2008), Holton (2003), Kelly et al. (1993), Nola and Irzik (2005), Ogborn (1995), Roth and McGinn (1998), and Slezak (1994a, b).

[21] With such a faculty, teachers could better function in their role as *mediator* between the scientific establishment and their pupils, also between public discourse about science with pupils or adults not conversant either how science evolves or the nature of modern techno-science (see also Hodson 2009).

[22] The term "scientism" can be interpreted in different ways; most construe it negatively (Bauer 1992; Haack 2003; Habermas 1968; Matthews 1994a/2014). Nadeau and Desautels (1984) attribute five components. Irzik and Nola (2009) are careful to distinguish legitimate scientific worldviews from illegitimate *scientistic* ones: "A scientific worldview need not be scientistic. Scientism, as we understand it, is an exclusionary and hegemonic worldview that claims that every worldview question can be best answered exclusively by the methods of science… that claims to be in no need of resources other than science. By contrast, a scientific worldview may appeal to philosophy, art, literature and so on, in addition to science. For example, scientific naturalism can go along with a version of humanism in order to answer worldview questions about the meaning of life."

outside authority), the ability to freely make use of one's own faculty of reason, to "have courage to use your own understanding!"(Kant 1784). This ambition is inherent of course to the *liberal education tradition* (Anderson 1980; Carson 1998; Matthews 1994a; Stinner 1989), the objective sought after when teachers desire students "think for themselves"—easily an identifiable historical goal of science education (DeBoer 1991, 2000; Schwab 1978). This is inclusive of the newer critical thinking movement (Bailin 2002; Siegel 1988, 1989; Smith and Siegel 2004). The primary focus here, however, is upon the further development of teachers' critical thinking and competence and their own capacity to judge not only curricular and policy documents, but above all their pedagogy, epistemological assumptions, and educational beliefs (whether implied by their textbooks, e.g., naïve realism, inductivism, pseudo-history, or proposed by science educational literature, e.g., STEM, STSE, constructivism, postmodernism, science for social action). The topic of *critical thinking* is well-trodden ground in philosophy of education, although researchers seldom avail themselves of this literature (Bailin and Siegel 2003; Siegel 2003).[23]

Finally, as Wittgenstein (1953) stated, philosophy can even be *therapeutic*. Implied for our theme, this means it can alert science teachers to implicit *images* of science and philosophies of education they may hold unaware. Perhaps they have internalized these through practice or originally picked up through teacher training from university professors promoting their own pet educational ideas and theories. Indeed, the teacher may have developed strong opinions about HPSS or "social justice" topics, "but the point of education is to develop students' minds, which means giving students the knowledge and wherewithal to develop informed opinions" (Matthews 1997, p. 171). In any case, translating Pierce's statement above with science educators in mind, one can write: "Find a science educator who proposes to get along without any philosophy-of-education … and you have found one whose goals, perceptions and methods are thoroughly vitiated by a crude and uncriticised one with which they are packed."[24] While the textbook epistemology is often concealed, a teacher's epistemology and educational theory is usually pieced together during their career and rarely made explicit.

In summary, philosophy cannot be gone around, for as a discipline of critical inquiry, it allows analysis into curriculum, textbooks, learning, best practice, and identity. Relooking at our previous PSE triangle (Fig. 39.1), this includes (i) offering conceptual clarity; (ii) unmasking ideologies (social, political, educational); (iii) sorting out foundational aims, values, and teacher identities; (iv) providing perspectives and theoretical frameworks, as well as synoptic and integrative approaches; and (v) possibly even utilizing *creative* theorizing as solutions to pressing problems (discussed below on educational theory).

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[23] Refer to the chapter contribution in this Handbook.

[24] What is being suggested here can be taken to correspond with a key objective of critical pedagogy, popularized by the Marxist teacher educator Paulo Freire (1970), their advance to "critical consciousness."

39.4 Philosophy of Education and Science Education

Philosophy of education, as mentioned, is a branch of philosophy. It seeks to address questions relating to the aims, nature, and problems of education. As a discipline it is "…Janus-faced, looking both inward to the parent discipline of philosophy and outward to educational practice … This dual focus requires it to work on both sides of the traditional divide between theory and practice, taking as its subject matter both basic philosophical issues (e.g., the nature of knowledge) and more specific issues arising from educational practice (e.g., the desirability of standardized testing)" (Siegel 2007). Thoughtful consideration of educational practice and assessing science curriculum is normally considered part of a teacher's professional competence; hence, some sort of philosophical thinking can be justifiably attributed to educators and researchers. What is of issue is the view that science educators can be encouraged to philosophize on a broader and systematic scale, and they can profit from philosophy of education (PE) studies (using their in-depth deliberations on theory and practice).

39.4.1 The Neglect of Philosophy of Education

If as Aristotle (1998) had intimated (by the opening quote) philosophy begins when one is filled with wonder—a state of being which can arise when confronted with some dilemma (hence one's *lack* of knowledge)—then the neglect to articulate a *systematic philosophy of* (PSE) for one's own science pedagogy (let alone the research field) causes one to ponder why so little effort and time have been invested into the subject. The consequences have not been a minor matter—confusion over educational *aims* including the "science literacy" debate, its meaning and competing "visions"[25]; science education's dependence on socio-utilitarian ideologies and competing group interests; science teachers' confusion about their identity and purpose, including the divide between belief and practice; etc.[26]

Jenkins (2001) has rightfully complained the research field is too narrowly construed and suffers from "an over-technical and over-instrumental approach" at the expense of other perspectives, such as neglecting historical studies. Although some recent research work can be taken as mitigating this charge (Gilead 2011; Jenkins 2007; Olesko 2006), even his perceptive critique had failed to mention the worth of

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[25] Science education to this day has been unable to resolve the principal dilemma concerning the conflict of the two competing "visions" of its purpose (hence competing conceptions of "scientific literacy"). Roberts (2007, p. 741) admits the community must "somehow resolve the problems associated with educating two very different student groups (at least two)."

[26] Refer to Aikenhead (1997, 2007), Bybee and DeBoer (1994), Donnelly (2004), Donnelly and Jenkins (2001), Pedretti et al. (2008), Schulz (2009a), Shamos (1995), Witz and Lee (2009), and Yager (1996).

philosophical studies. The inertia of traditionalism[27] at the upper levels had prompted Jenkins surprising call for a "paradigm shift," as mentioned—but this is serious talk, nothing less than a plea for somber philosophical contemplation and reorientation. Even at the postsecondary level, the need to reform introductory science classes has received increased attention especially with some new findings in Physics Education Research (PER) indicating that the dominant textbook- and lecture-based instruction in large classrooms is unwittingly producing an antiscientific mind.[28] The appearance in time of three identified public "crises" regarding school science education (1957, early 1980s, late 1990s; Schulz 2009a) and the apparent inability of different "reform waves" to provide for major, long-lasting changes could in turn suggest that a shift towards a more concentrated educational-philosophical examination of the problems lies at hand. It can be argued that the general lack of consideration of educational philosophy and theory, that is, a *philo-educational failure*, could help account for why curricular reforms are particularly vulnerable to the political whims (or "ideologies") of various stakeholder groups, an enduring situation several researchers have taken notice of.[29] It could, for example, better inform policy deliberations when diverse stakeholders are at odds over what should "count" as science education (Fensham 2002; Roberts 1988).[30]

Fensham (2004) argues in his important book *Defining an Identity* that science education is still searching for ways to characterize its own "identity" as a

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[27] Grade 11 and 12 specialist science courses continue to serve primarily a gatekeeping function for college and university entrance, and their purpose, structure, and content usually replicate first-year tertiary courses—their chief rationale is exclusively with "science for scientists," and not concerned with the large majority who will not specialize. In other words, as induction into pure academic science but at the neglect (if not deliberate omission) of discussing (never mind integrating), the epistemologies, social practices, and proper history of the sciences—otherwise termed *nature-of-science* perspectives (Hodson 2008; Irzik and Nola 2011; Lederman 2007; Matthews 1998a). Reform movements like *Science-Technology-Society* (STS), *Science-Societal Issues* (SSI), and (lately) scientific argumentation studies have been attempting to counter this dominant school paradigm for some time but continue to make only small inroads.

[28] Yet despite these disturbing findings, researchers in these newer fields of study (also Chemical Education Research) still struggle uphill for respect and acceptance in their academic departments, where educational studies and research continue to be afforded a low priority (Gilbert et al. 2004; Hestenes 1998).

[29] See Aikenhead (2006), Bencze (2001), Donnelly and Jenkins (2001), Fensham (2002, 2004), Roberts (1988), and Roberts and Oestman (1998). Laugksch (2000) draws attention to different social group interests in defining "science literacy." Ernest (1991) also identifies several interest groups as determinants of mathematics education.

[30] Fensham's (2002) paper "Time to changing drivers for scientific literacy" (movement away from the academic driver to "social" and industry-based drivers) provoked a lively response from researchers about the "educo-politics" of curriculum development, especially about what role academic scientists should play, if any (Aikenhead 2002; Gaskell 2002); such a suggestion though would reorientate science education back towards the recurrent (and contentious) "social relevancy" goal and the progressivism of Deweyan-type philosophy (Darling and Nordenbo 2003; DeBoer 1991)—whose educational theory is often concealed. It may even involve a Faustian bargain with industrial- and vocational-driven interests. Gaskell believes the risk is worth it. But given the complexity of techno-science and the great diversity of vocations and business interests today leaves one wondering if any sort of meaningful consensus on curriculum is achievable, even locally.

discipline. (His comprehensive survey canvasses the views and backgrounds of 76 prominent researchers in 16 countries, active from the 1960s to the present.) One would like to suppose that helping to define such an identity would include philosophy, especially a *philosophy of science education* (PSE). And it is not only the identity of the *discipline* that is of issue here, but as referred to in the previous section, that of the classroom professional as well. Hence, it might appear the time has come for science education to return to some philosophical ground work, to come to value philosophy of education (PE), and, in turn, for the research field to inaugurate and develop a new *fourth area* of inquiry—philosophic-historical. This one added next to the common three of quantitative, qualitative, and emancipatory, in support of arguments made previously by others for its development as a "mature discipline" (Good et al. 1985; Kyle et al. 1992).

But Fensham's book, with the sole entry of PE on one page alone (where the significance of Dewey is also cited), bears ample evidence of the disregard of this subject topic for researchers and science teachers alike.[31] One can infer from the evidence to date that the worth of any sort of meta-analysis of their discipline and pedagogy seems to hold little value for the majority, thereto the need to bring systematic educational-philosophical reflection to bear on research, curriculum, and teaching.

This claim is further evidenced by a simple perusal of research *Handbooks* published thus far, where the subject of philosophy of education (including topics "philosophy," "educational theory," "curriculum theory") is missing entirely (Fraser et al. 2012; Abell and Lederman 2007; Fraser and Tobin 1998; Gabel 1994). This absence is likewise attested by recent publications of European Handbooks of research in the field (Boersma et al. 2005; Psillos et al. 2003). Crossing over the other way, most handbooks or "guides" of philosophy of education (PE) exhibit the same paucity by avoiding science education, though art education, moral education, knowledge, feminism, postmodernism, critical thinking, and critical pedagogy as subjects remain prevalent.[32] Two exceptions exist: Curren (2003) and Siegel (2009). Comparing both fields, the claim is reinforced by an inspection of the respective leading research journals in both philosophy of education and science education for the past 30 years, which exhibit an almost complete disregard of the opposing field (barring exceptions). What one finds is that only a handful of philosophers write for the science education journals, and even fewer science educators publish in philosophy of education.[33]

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[31] Fensham in fact suggests that it is the "dominance of psychological thinking in the area" which attests to why Dewey is *not* cited more frequently among respondents in the USA (still the most prominent philosopher of education linked with science education in North America).

[32] Important works are Bailey et al. (2010), Blake et al. (2003), Chambliss (1996a), and Winch and Gingell (1999).

[33] Authors in alphabetical order include Bailin, Burbules, Davson-Galle, Garrison, Grandy, Hodson, Matthews, McCarthy, Norris, Phillips, Scheffler, Schulz, Siegel, and Zembylas (see respective references).

If an examination of the preparation of science education researchers is any indication of the kind of academic preparation science teachers themselves receive (before they become researchers), then another look at Fensham's *Identity* book as commented on by Matthews (2009b, p. 23) is revealing. He notes that "the interviews reveal that the overwhelming educational pattern for current researchers is: first an undergraduate science degree, followed by school teaching, then a doctoral degree in science education" (citing Fensham 2004, p. 164). As Matthews observes, unfortunately "most have no rigorous undergraduate training in psychology, sociology, history or philosophy." Fensham himself comments that at best, "as part of their preparation for the development tasks, these teachers had opportunities to read and reflect on materials for science teaching in schools and education systems that were different from their own limited experience of science teaching."[34] Matthews concludes that Fensham's survey reveals an overall "uncritical adoption of idealist and relativist positions" among researchers and that poor academic preparation is a reason why "shallow philosophy is so evident in the field."[35] It certainly appears as if the inadequate science teacher preparation in philosophy of education is mirrored by the widely recognized fact of the inadequate preparation with respect to philosophy, history, and sociology of science.

39.4.2 Historical Background of Philosophy of Education and Science Education

With an eye fixed solely on the mutual historical developments of both fields, this neglect is rather difficult to explain especially because science education is after all about *education*, with natural focus on the science specialty. But philosophy and education have roots that are intertwined in history long past, convincingly traceable back to Plato (*Meno*; *Republic*). Every major philosopher in the Western tradition from Plato (in Ancient Greece) to Kant (European Enlightenment) to Dewey (modern industrial America) has proposed educational projects of some kind (Rorty 1998; Frankena 1965; Whitehead 1929). As Amelie Rorty correctly points out (1998, p. 1): "Philosophers have always intended to transform the way we think and see, act and interact; they have always taken themselves to be the ultimate educators of mankind." Understood in this way, Dewey was on the mark when he famously phrased the view that the *definition* of philosophy is "the theory of

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[34] Matthews comments this may be the significant reason why the science education research literature "is dominated by psychological, largely learning theory, concerns" (ibid). Others have also cited the domination of psychology and conceptual change research (Gunstone and White 2000; Lee et al. 2009).

[35] The typical tendency is to adopt philosophical or ideological views from well-known authors outside the field but often not accompanied by critical appraisal of such authors: "… the work of Kuhn, von Glasersfeld, Latour, Bruner, Lave, Harding, Giroux and others is appropriated but the critiques of their work go unread: it is rare that science education researchers keep up with psychological and philosophical literature" (ibid, p. 35).

education in its most general phases" (1916, p. 331)—although most professional philosophers today would probably not construe it as such.

It was the Enlightenment's "project of modernity" (Habermas 1987)—first begun in the seventeenth century—that was expressly formulated as an *educational project* and which saw in the new science of the day an instrument for personal and sociopolitical liberation (Gay 1969; Matthews 1989). It is of course in full awareness of this intellectual and cultural heritage that postmodernists like Lyotard (1984) would outright dismiss the "grand narrative" of this project with its associated role and *image* of science as an emancipatory and positive force, including those science educators convinced by his critique (Loving 1997; Nola and Irzik 2005; Rorty 1984; Schulz 2007).[36] In fact the popularity of strands of post-structuralist Foucault, 1972/1989, 1980; Nola, and postmodernist thinking among some researchers bears witness to the recent discovery of the value of philosophy for the field (Zembylas 2000, 2006).

Looking much further back in time (again at the *Metaphysics)*, Aristotle identifies the man of knowledge—one who has attained expertise either via *techné* or *theoria* (instrumental or theoretical reason)—as the one who is plainly able to teach what he has learned and as such draws one distinguishing feature of the philosopher. To be a philosopher was to be a teacher. Conversely, to be a teacher implies one must do philosophy (of one form or other). Science educators seen in this light are inescapably located within a venerable philosophical tradition *along with* the newer scientific one which they usually and exclusively tend to associate themselves with—though, here too, not fully aware of the latter's cultural roots and significance.

The first mention of philosophy of education as a distinct field of study was in Paul Monroe's *Cyclopedia of Education*, published 1911–1913 (Chambliss 1996b). Philosophy of education, depending upon the given nation and its educational traditions, can be viewed as a relatively new discipline or not. As Hirst (2003, p. xv) points out, "philosophical inquiry into educational questions" was more established in the USA, Germany, and Scandinavia, whereas in the UK philosophy of education as a discipline first came into its own in the 1960s. It was dominated by analytic philosophy and accounts of schooling, although in ethics Kantianism was the major influence. In the USA, the *American Philosophy of Education Society* had already been founded earlier in 1941, along with the Deweyan journal *Educational Theory* in 1951. It was the pragmatist philosopher and educationalist John Dewey in his influential work *Democracy and Education* (1916/44) who had conceived of PE to be a study worked out on an experiential basis—in other words, that educational ideas were to be applied and tested in practice. He also considered that theory and

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[36] Related to this topic is the question of what worldview(s) science assumes or requires in order to be sustained, hence which one(s) educators need to be supportive or cognizant of (Matthews 2009a). This further raises the question of the *universalism* of "Western science," whether or not its knowledge and truth claims are necessarily culturally confined, or merely *evolved*. Disputes over the interpretations of "multicultural science" will not be addressed here, but again science educators require philosophical training in order to adequately tackle these controversial topics. Philosophical treatment of this subject can be found in Hodson (2009), Matthews (1994a), Nola and Irzik (2005), and chapters in this Handbook.

practice were interdependent in a kind of feedback loop mutually learning from and reinforcing each other. This stood in contrast to the earlier views of the Englishman Herbert Spencer who instead conceived of education as an inductive science and where PE would serve as a kind of scientific method.

Alternatively, on the continent in Northern Europe, very different views about education had been developing. The ideas of Kant, Schiller, Herder, Herbart, and others had contributed to create the influential *Bildung* paradigm in the nineteenth century.[37] It has become established as the *Bildung/Didaktik* tradition whose conception of education dominates the German-speaking world and the Nordic countries.[38] Today this paradigm is not without its detractors, for by the 1960s this tradition had itself begun to clash with the "critical theory" of the Frankfurt school (Blake et al. 2003; Blake and Maschelein 2003; Smeyers 1994). It continues to engender much debate among educational thinkers and philosophers alike, both in Europe and English-speaking countries. Thereto, advocates of both traditions—Anglo-American "curriculum" and *Bildung/Didaktik*—came together in the 1990s to open dialogue comparing the relative benefits of each (Gundem and Hopmann 1998; Jung 2012; Vásquez-Levy 2002).

The *Bildung* paradigm itself actually represents an *educational metatheory* (Aldridge et al. 1992), a type of "grand theory" in education of which very few have been constructed in modern times (inclusive of Dewey and Egan; Polito 2005). It immediately raises the question of the worth and relation of educational theory to practice, whose merits are currently being contested in philosophy of education (Carr 2010).

The direct link between *Bildung* and science education[39] has been drawn only recently, notably in Fensham's *Identity* Book (2004) and by Witz (2000).[40] Fensham provides a highly informative discussion, explaining the concept and significance of *Bildung* when contrasting the Norse/German tradition with the content knowledge-driven Anglo-American tradition. He contends that a serious shortcoming of the so-called "curriculum tradition" of the English-speaking world is its consistent disregard of metatheory (discussed further below).[41] *He advises science education*

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[37] The literature on *Bildung* and *Didaktik* is extensive. Some references to its historical development are Barnard (2003), Beiser (1998), Gadamer (1960/1975), and Schiller (1795/1993).

[38] "On the one hand, the concept *Bildung* describes how the strengths and talents of the person emerge, a development of the individual; on the other, *Bildung* also characterizes how the individual's society uses his or her manifest strengths and talents, a "social" enveloping of the "individual" (Vásquez-Levy 2002, p. 118). Given this interpretation, one could in fairness associate the values and aims of the *Bildung* tradition with two prevalent "curriculum ideologies" identified by Eisner (1992) as "rational humanism" and the "personal" stream within progressivism.

[39] Science education and *Bildung* in Germany have been examined by Benner (1990) and Litt (1963).

[40] One Canadian study involving science teachers had sought to fuse the *Bildung* ideal with the STS paradigm and cross-curricular thinking (Hansen and Olson 1996).

[41] "In the one, the maturing young person is the purpose of the curriculum. In the other, the teaching of subjects is the purpose. In the one case, disciplines of knowledge are to be mined to achieve its purpose; in the other, disciplines of knowledge are the purposes" (2004, p. 150).

should acquire one. The same arguments have long been raised in Germany by Walter Jung (2012).

Another interesting aspect about the *Bildung* paradigm can be noted: it exercised an indirect influence via Herbart's ideas on the philosopher-scientist Ernst Mach. While Mach's impact on Einstein's thinking is generally recognized, his educational ideas are hardly known in the English-speaking world. Already back in the late nineteenth century, he had been politically active for educational reforms, including improving teacher education, and is credited with founding and coediting the very first science education journal in 1887 *Journal of Instruction in Physics and Chemistry* (Matthews 1990b, 1994a). Siemsen and Siemsen (2009) argue his rediscovery at present could provide significant contributions to current European reform efforts.

On a final note, for the English-speaking nations, the USA was in the forefront of the establishment of both disciplines (science education and philosophy of education) that have developed in tandem—simultaneously but separately in the early twentieth century. One would think that because of this pedigree, and in some cases of clearly overlapping interests (as exhibited in the important case of Dewey), science education would be more cognizant, and science teacher training more reflective, of their common roots. Unfortunately, on this matter science education seems to suffer amnesia on both counts, for if it can be admitted that "philosophy of education is sometimes, and justly, accused of proceeding as if it had little or no past" (Blake et al. 2003, p. 1), then this certainly rings true of science education.[42]

The call for a philosophy *of* science education (PSE) is not only to raise awareness of this forgotten earlier period, but *to identify the need to create a subdiscipline within educational studies* that, although new, nonetheless has substantial historical roots going back into the science-educational but especially the philosophical-educational past.

Why science educators do not associate themselves just as intimately with philosophy of education is a fascinating question, one that cannot be pursued here. It almost certainly has a lot to do with several factors (such as the prestige of science in society, how disciplinary knowledge is structured, how their own university science education proceeded, and, not least, how they were trained as educational professionals).[43] What is called "foundations in education" courses, which usually include studies in the history and philosophy of education, are often optional for preservice science teachers, depending upon the prerequisites of their attending institutions.[44]

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[42] Jenkins (2009) notes the same problem with reform movements and policy documents. This complaint (although dated but still relevant) was earlier attested by DeBoer in his Preface to his insightful *History of Ideas in Science Education* (1991).

[43] Roberts (1988, p. 48) draws attention to where teacher *loyalties* commonly lie: "The influence of the subject community is an especially potent force in science education. In general, the 'hero image' … of the science teacher tends to be the scientist rather than the educator [or philosopher]."

[44] Hirst (2008b) has recently complained that in some countries such as England, there are now moves afoot to delist such courses for teacher training altogether. It would not be a stretch to conclude that

39.4.3 Philosophy of Education Today

Coming at last to the present historical culmination, philosophy of education has today progressed to become a respectable, established subdiscipline in philosophy. It comprises evolving research fields, a sizeable literature, professorial chairs, professional associations (e.g. PES), and several leading journals.[45]

There now exists two *Handbooks* (Bailey et al. 2010; Siegel 2009) but also a *Guide* (Blake et al. 2003), *Companion* (Curren 2003), and *Dictionary* of key concepts (Winch and Gingell 1999). An *Encyclopedia* of PE is also on hand (Chambliss 1996a). These can be sought out by science educators to familiarize themselves with the current discussion, inclusive of disputes regarding different topics of individual interest to them. Several newer and older *Introduction* texts are also available (e.g., Barrow and Woods 2006/1975; Tibble 1966), including Carr (2003) and Noddings (2011). For educators seeking immediate information, several encyclopedia articles exist providing succinct, comprehensive overviews of PE (accessible online: Phillips 2008; Siegel 2007).

39.4.4 The Value of Philosophy of Education

Philosophical questions bearing on the different facets of science curriculum, teaching, and learning must be addressed and inspected by the thoughtful educator:[46] questions pertaining to (i) chief educational goals, content selection, and course objectives, or (ii) assessing learning theories, or (iii) bearing on nature-of-science- and techno-science-related issues—thereto, the character of scientific research, knowledge, and societal applications as related to curriculum or policy reforms. Hence, questions also pertaining to who enacts and benefits from such reforms with respect to interests and ideologies. And all this often in spite of, not because of, state-mandated and prepackaged "content knowledge" curricula:

> What are the aims and purposes of science education? What should be the content and focus of science curricula? How do we balance the competing demands of professional training versus everyday scientific and technological competences versus the past and present interactions of science with society, culture, religion and worldviews? What is the structure of science as a discipline and what is the status of its knowledge claims? What are the ethical constraints on scientific research and what are the cognitive virtues or intellectual dispositions

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such a downgrade in the general value of philosophy-of-education cannot fail to negatively impact science teacher professional development.

[45] The leading journals of the English-speaking world are *Studies in Philosophy and Education, Educational Theory, Educational Philosophy and Theory,* and *Journal of the Philosophy of Education.*

[46] Some classroom case examples are Hadzigeorgiou et al. (2011), Kalman (2010), and Ruse (1990). Bailin and Battersby (2010), Giere (1991), and Kalman (2002) offer science teacher educators rich material for enhancing science subject-related critical thinking:

> required for the conduct of science? What is the meaning of key scientific concepts such a theory, law, explanation, and cause? (Matthews 2002, p. 342)

If it is indeed true, for example, that precollege and first-year college level science courses are primarily about "technical preprofessional training," then vital questions need to be asked about what differences should exist between training and education in science. It raises cultural, epistemological, and political questions about the nature of school science: whether, for instance, it is truly reflective of the nature of science (in some form) or more reflective instead about courses performing a "gatekeeping" function by limiting access to higher education (a sociopolitical role)—this in turn reflecting norms of school culture and assimilation (as critical pedagogy perspectives contend).[47] Does a hidden cultural bias exist (as "cultural studies" perspectives contend)? Should the worth of school physics and chemistry education, say, be mainly determined by "political/instrumental value" (prerequisites to college entrance courses; Aikenhead 2006)? If so, this would raise more disturbing questions about the nature of, or links between, socialization, training, and perhaps indoctrination (into scientism). There can be little doubt that in such cases a given "vision" of what constitutes "science education" is in place (with hidden "companion meanings"; Roberts and Oestman 1998).

At minimum it should raise questions about subject epistemology or the preeminent *value* placed upon a certain kind (Gaskell 2002). Such topics, though, have been a staple of PE disputes for quite some time—inclusive of deliberating the difference between hidden aims and genuine educational aims of curriculum and schooling (Apple 1990; Posner 1998), or the differences between education and indoctrination (Snook 1972). Not to forget, previous science education reforms have too often been associated with several past "crises" (as cited) which were themselves linked with wider socioeconomic problems in society: were these just pseudocrises manipulated by science education stakeholders and their interest groups? What educational values/views inform such groups and their policies?[48] Again, similar questions are addressed in PE.

39.4.4.1 Philosophy of Education and the Nature-of-Science Debate

Just focusing on one fundamental topic, the *nature-of-science* (NoS) debate, and zeroing in only on one aspect of this debate, the key question is: "who defines science for science educators?" The scientific experts within isolated academic disciplines (as is common)? Philosophers of science? Historians? Sociologists? Or those within cultural and women's studies? Postmodernist-type thinkers and critics?

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[47] "Domination, resistance, oppression, liberation, transformation, voice, and empowerment are the conceptual lenses through which critical theorists view schooling and pedagogy" (Atwater 1996, p. 823).

[48] Different kinds of answers are provided by Aikenhead (2006, 2007), Apple (1992), Bencze (2001), Donnelly and Jenkins (2001), Gaskell (2002), Gibbs and Fox (1999), Klopfer and Champagne (1990), Roberts and Oestman (1998), Schulz (2009a), and Zembylas (2006).

Or possibly students and teachers themselves, according to some versions of social constructivist theory?

The NoS topic alone has been recognized as one chief aim of science education for over 50 years, yet to this day, there exists a poor record of achievement worldwide (Lederman 2007). This fact is due to several interrelated causes, not least of which is the entrenchment of traditionalism (conventional discipline-based paradigm)—but moreso the reality that NoS is itself a contested field in HPSS studies. The "science wars" (initially launched by the Sokal hoax 1996a, b) and their aftermath have made the issue public, and science teachers are inadvertently involved in a contest that is being fought in the academy.[49] Researchers can certainly be found on either side, running the gauntlet from "positivism to postmodernism" (Loving 1997; Turner and Sullenger 1999).[50]

These polarized camps have made the business of science education a messy and complicated affair—it has become increasingly difficult to navigate a pedagogical course between competing views "from diehard realism to radical constructivism" (Rudolph 2000, p. 404). At best consensus can be found that several common classroom *myths* must be exposed, including talk of "scientific method" (Bauer 1992; Feyerabend 1975; Hodson 1998; Jenkins 2007). Teachers clearly require substantial philosophical background to familiarize themselves with the issues, but even *if* consensus could be achieved (which seems unlikely), the question cannot be solely confined and determined on HPSS grounds. This decision would leave entirely untouched the related *pedagogical question* how that (would be) conception of science plays a role in the education of the student, as to what educational *aim(s)* school science is ultimately expected to achieve.[51] In other

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[49] For examples of teachers caught in the debate, see Sullenger et al. (2000) and Witz and Lee (2009). For different perspectives on the debate in the academy, see Brown (2001), Giere (1999), Gross et al. (1995), Laudan (1990), Nola (1994), C. Norris (1997), Siegel (1987a, b), and Sokal and Bricmont (1998).

[50] Science educators continue to quarrel whether basic NoS statements *can* or *should* be defined, even where a measure of recognized consensus is said to exist—inclusive of those now written into global policy documents. The dispute centers on how to determine "consensus" (among which experts?), or questions regarding disciplinary distinctions, or about NoS cultural dependence on "Western" science and Enlightenment traditions, among others (Hodson 2008; Irzik and Nola 2011; Matthews 1998a; Rudolph 2000, 2002). Good and Shymansky (2001) make the case NoS statements found in "standards" documents like NSES and *Benchmarks* could be read from opposing positivist- or postmodernist-type perspectives.

[51] This viewpoint aligns to an extent with Hodson's view (2009, p. 20) except for the fact he ignores relating his desired outcomes to educational philosophy and theory: "In my view, we should select NOS items for the curriculum in relation to other educational goals … paying close attention to cognitive goals and emotional demands of specific learning contexts, creating opportunities for students to experience *doing* science for themselves, enabling students to address complex socio-scientific issues with critical understanding…." On what philo-educational grounds the selection is to be undertaken, we are not told though he considers students' "needs and interests" (overlap with progressivism?), views of experts ("good" HPSS—the Platonic knowledge aim?), and "wider goals" of "authentic representation" of science and "politicization of students." His lofty ambition for science education (thus his notion of "literacy"), however, includes too many all-encompassing and over-reaching objectives. These must clash and become prioritized (or so it seems) once his

words, for the educational setting, the question "what counts as science?" must be allied with "what counts as science education?"[52] The historian may have something to say (e.g., correcting pseudo-history in textbooks), at other times the philosopher of science (e.g., correcting misleading epistemology inherent to textbooks), other times the sociologist, etc., each depending upon the context of instruction and in coordination with desired educational objectives and policy deliberations of stakeholders.

The issue is precisely that subject content (inclusive of disciplinary structure) must be "problematized" during curriculum decision-making, and for *two* reasons:

(i) It must be broadened to function as a more authentic and appropriate knowledge base.
(ii) It must be transposed into a form that considers the culture and age developmental stage of learners along with desired educational aims (Englund 1998; Schulz 2011).

That the curriculum needs to be made problematic implies that a *philosophical* (and not just instructional) problem initially lies at hand which requires resolution. This problem lands us squarely in philosophy of education (PE) territory. It requires a close linkage of questions found in PS with those found in PE (the base of the triangle in Fig. 39.1). The philo-pedagogical problem concerns the appropriate or *best didactic transposition* of epistemic content knowledge (CK) into an appropriate form accessible to the learner in accordance with educational aims and theory.[53] There are some educational thinkers who argue this cannot be suitably achieved without educational *metatheory* (Carr 2010; Dewey 1916/1944; Egan 1997).

As an example, while a teacher's content knowledge (CK) in chemistry may need to be better informed by research in the philosophy of chemistry (one crucial component of PSE would involve stressing this factor), nonetheless a PSE is more concerned with how such CK can be made to fit with the requirements of an educational metatheory and its concern with the cognitive-emotive *developmental stage* of the learner, with respect to this subject matter. In other words, a teacher's CK and the curriculum are not at the forefront for learning science (although they are invaluable dimensions), as is commonly done. Rather, they are evaluated in light of philosophy of education and the learner's age developmental mind-frame as befits

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three stated criteria for subordinating goals force them under his socio-techno-activist umbrella of politicizing students—the ghost of Dewey beacons.

[52] The focus here is on the normative nature of the question (i.e., what do policy documents, researchers, or theorists stipulate?), as opposed to the empirical (i.e., what is going on in classrooms now?).

[53] This important topic is too often overlooked in curriculum theory or in the science education literature. See Fensham (2004), Geddis (1993), Klafki (1995), Lijnse (2000), Schulz (2011), Vásquez-Levy (2002), and Witz (2000); Dewey, Mach, and Schwab all in their day also identified the issue that the logic of the discipline does not conform with the psychologic of learning the subject matter of the discipline. Thereto, Aikenhead (1996) has argued that learning science involves a culturally rooted "border-crossing" on the part of the student, to negotiate the transition from the personal "lifeworld" to the "school-science world."

what it means to *educate* a person in the sciences. This emphasis necessarily shifts the focus to the substance of a teacher's pedagogical content knowledge (PCK) and educational philosophy.

If, say, NoS knowledge is taken to be an *end* (an aim in itself), then an implicit "philosophy" would be "academic rationalism" (Eisner 1992)—whose objective could be associated with "knowledge-for-knowledge sake," building "mind" (possibly even critical thinking), and likewise similar-sounding ideals coupled to a typical knowledge-driven educational metatheory (Egan identifies it with Plato's historic project).[54] This *can* equally be squared with science teaching within the conventional academic paradigm, though providing subject content with *context* (Roberts "vision I"); on the other hand, NoS combined with "critical thinking" as *means* to create critical-minded citizenry to strengthen democracy in society would couple NoS teaching with Deweyan-type educational metatheory (Egan identifies this educational tendency with a form of socialization; Roberts "vision II"). There are tensions here which may not be reconcilable[55]—tensions also inherent to liberal education (e.g., aims for the individual and society can clash considerably); they are certainly topics of concerned debate in PE. Not to be forgotten, there are those who wish to teach NoS because it stands alone—the *intrinsic* worth to learn about authentic science (or science as a cultural force); others however see it subservient to other ends—for advancing critical thinking (itself), or chiefly addressing science-societal issues (Zeidler et al. 2005), or yet again, for emancipation (critical pedagogy) and sociopolitical action (Hadzigeorgiou 2008; Hodson 2009; Jenkins 1994).[56]

What is really of issue here, though hardly recognized, is how (and which) *epistemic aims* of science education (e.g., knowledge, truth, justification)[57] can or should be met, either apart from, or linked with, or perhaps subordinated to, other identified *moral* and *political* aims of education (e.g., autonomy, human flourishing, citizenship, social justice).[58] A common and depressing feature of several reform programs (e.g., STS, SSI, sociopolitical activism) is the notable confused state of their several suggested educational aims. Moreover, it can be asserted that such avowed and increasingly popular projects for science education as identified presuppose educational metatheory of some kind, whose existence is either assumed or overlooked.[59] Engagement with philosophy of education debates about,

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[54] See discussion on the topic of epistemic aims by Adler (2002), Hirst (1974), and Robertson (2009).

[55] See discussion in Egan (1997) and Pring (2010). Smeyers (1994) discusses the European account.

[56] Driver et al. (1996, pp. 16–23) offer five rationales for teaching NoS in classrooms, yet they either assume or overlook their dependence upon different, prior educational theories.

[57] See Nola and Irzik (2005), Robertson (2009), and Siegel (2010) for discussion of these subjects.

[58] See Brighouse (2009) and Pring (2010) for discussion of these subjects. Donnelly (2006) only scratches the surface of the problem with his defined dual clash between "liberal" and "instrumental" educational aims behind community reforms.

[59] This remark also targets research concerning situated cognition models, where it has often been asserted; practice was either *prior* to theorizing or *without* theory. See critiques of Roth by Sherman (2004, 2005).

and analyses of, *indoctrination* can be an antidote to such political-activism programs simply replacing unthinking science lessons with uncritical acceptance of whatever causes teachers or researchers might be energized about. As Erickson has stated (2007, p. 33), the science education community "needs to develop pedagogical models that make explicit the normative premises about aims" in its discourse on scientific literacy.[60] Whenever the topic of educational aims arises, the neglect and need of philosophy of education become only too evident.[61] The time has come for the community to strive for clarity and prioritization concerning which fundamental aims the field can and should achieve (Bybee and DeBoer 1994).

In any event, NoS raises foundational *philo-educational* questions: "What is the ultimate aim of science education?" (or, e.g., of physics education?). "What does it *mean* to be educated in science?" "How is such an education related to human flourishing?" These should ideally be addressed before the subsidiary question "what do we educate people in science *for*?"—often the common starting point of curriculum thinking and policy decision-making, which begins first with the prior value, with its linked presumption of the overall importance, of *social utility*. (The difference so stated is one of choosing between deontologic or teleologic rationales.) The former should not be approached as "mere academic questions" during teacher preparation, for they aim at the heart of what the profession and teacher identity is all about. Yet it should be clear that they cannot be answered without reference to educational philosophy and theory—while the utility rationale, alternatively, presupposes a particular one. In other words, it requires of the science educator a *philosophical valuation* of subject content and aims and an awareness of the broader educational purpose of the science educational field, including some personal positioning among available educational/curriculum theories (Scott 2008).

39.4.5 Overview of Philosophy of Education Subjects and Questions

It is the view of the present author that teachers as well as researchers when becoming more conversant with the ideas and disputes as argued by philosophers of education will help them (at minimum) gain insight and perhaps (at maximum) resolve

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[60] He continues: "Too often we try to simply derive pedagogical practices from theoretical positions on learning, or diversity, or language, or the latest research on the functioning of the brain, etc." (ibid).

[61] An example of the confusion which results in science education research when PE is ignored is the paper by Duschl (2008). Here empirical research from the learning sciences and science studies is confused with educational goals, which must be chosen on a normative basis. Such research may very tell us *how* students (and scientists) learn but expressly not *why and what* goals they *should* learn. And to argue for a "cultural imperative" is to *make* a normative claim extrapolated from such research—one is dabbling in PE without its recognition. Moreover, whether the avowed economic, democratic, epistemic, "social-learning" goals, etc. (as they have been historically articulated for the field) can be "balanced" as Duschl simply assumes is by no means obvious—PE debates show quite the opposite (Egan 1997; Levinson 2010; Schulz 2009a).

problems related to issues of *common interest* (the nature and kinds of aims; the nature of language and learning, knowledge and truth, educational theory; feminism, multiculturalism; education for citizenship; critical thinking; ideology, interests, and curriculum; indoctrination, etc.). The field of philosophy of education is a veritable mine of ideas, posed problems, and suggested solutions. This holds true whether the *approach* to PE is simply to:

(i) Study prominent philosophers and their views on education (e.g., Plato, Aquinas, Rousseau, Kant, Whitehead, Scheffler, Foucault)[62]

(ii) Study educational thinkers and their philosophical positions (e.g., Schiller, Herbart, Dewey, Peters, Freire, Hirst, Egan, Noddings)

(iii) Study sub-branches of philosophy and their relevance to education (e.g., philosophy of science, moral and political philosophy, or aesthetics)

(iv) Study "schools of thought" in education (e.g., idealism, realism, Thomism, Marxism, existentialism, critical theory, postmodernism)[63]

(v) Study the philosophical questions of ultimate concern (e.g., the nature of being, of knowledge and cognition, the ideal of an educated person, autonomy)

There is intellectual insight and pedagogical profit to be had in any of these approaches (Barrow 2010). For the more practical-minded science educator though, the approach to PE could imply instead a focus on specific, contemporary educational questions. Here Amélie Rorty's (1998, pp. 1–2) list of essential PE questions serves to illustrate the "down-to-earth" PE approach, when *transposed* onto science education:

> What are the directions and limits of public [science] education in a liberal pluralist society? … Should the quality of [science] education be supervised by national standards and tests? Should public [science education] undertake moral education?[64]… What are the proper aims of [science education]? (Preserving the harmony of civic life? Individual salvation? Artistic creativity? Scientific progress? Empowering individuals to choose wisely? Preparing citizens to enter a productive labor force?) Who should bear the primary responsibility for formulating [science] educational policy? (Philosophers, …, rulers, a scientific elite, psychologists, parents, or local councils?).[65] Who should be educated [in science]?[66] How does the structure of [scientific] knowledge affect the structure and sequence of learning? … What interests should guide the choice of [science] curriculum?

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[62] To name just some in the Western tradition; Eastern and other traditions have of course their own major philosophers who have concerned themselves with education.

[63] A classic source of material for this orientation are the essays in Henry (1955).

[64] As those in the *SocioScientific Issues (SSI)*, reform movement today insists (Zeidler and Sadler 2008).

[65] See DeBoer (2000), Fensham (2002), Gaskell (2002), Jenkins (1994), and Roberts and Oestman (1998), for responses to such questions.

[66] Recall the ongoing past disputes between "science for scientists" and "science for all" perspectives on curriculum, goals, and policy (ByBee and DeBoer 1994; DeBoer 1991). The most recent STEM reform movement in the USA can be justifiably accused of redefining science education as "science for engineers."

It is quite clear that common questions and concerns exist and one would have expected more cross-disciplinary discourse than has heretofore existed.

On the other hand, it is not here being suggested that a consensus is to be found among philosophers of education on such questions. In fact there are important disagreements and even diversity of interest and approaches to the solutions, as different PE "schools of thought" display (analytic, existential, phenomenological, postmodern, critical theory, etc.). Indeed, philosophy more often "divides" than it unites, and as one contemporary education philosopher admits: "missing in the present world of diversity of interests is the classic sense of a quest for philosophic unity" (Chambliss 1996b). As Scheffler stressed, "philosophies of" are not forged by some harmony of agreed-upon, sealed discourses. Instead they

> do not provide the educator with firmly established views … on the contrary, they present him with an array of controversial positions. But this array, although it does not fix his direction, liberates him from the dogmatisms of ignorance, gives him realistic apprehension of alternatives, and outlines relevant considerations that have been elaborated in the history of the problem. (Scheffler 1970, p. 391)

The point is not that some sort of philosophical unity should be either expected or had among philosophers or science educators, although of course consensus on common fundamental issues is to be desired. Rather, the nature of the discourse and sophistication of the debate can help illuminate those problems and issues which science educators are confronted by and continue to struggle with or have misconstrued, have overlooked, or for too long avoided.

39.5 Some Major Philosophy of Education Perspectives and Science Education

39.5.1 Educational Theory and Science Education

To talk of "educational theory" is first of all to recognize that it has undergone shifts in meaning ever since Western philosophy began contemplating educational matters in Ancient Greece. For the sake of brevity (and hazarding oversimplification), one charts a course from there to the current age by noting how its worth and purpose have undergone several changes, not only when specifying what *aims* to target, but *who* should carry the prime duty, namely, either philosophers, educationalists, or empirical scientists (Carr 2010; Phillips 2009).

The priority in Antiquity (Plato, Aristotle, Cicero) was to establish the grounds for knowledge to improve moral virtue (the "Good") but conceived more along a priori philosophical lines—hence the emphasis on reason and rationality. This tendency took "an empirical turn" with Rousseau, progressivism, and the rise of the scientific Enlightenment. This science-inspired propensity has continued right down to the primacy of developmental psychology in our age, "the view that the study of human cognition, emotional and social growth and learning ought to be scientifically grounded" (Carr 2010, p. 38). Largely lost sight of along the way was the previous prominence of moral virtue required to remodel society—reclaimed later in different guises by Deweyan theory (of social adaptation or reconstruction), critical theory/pedagogy, and *Bildung*. The postwar positivistic, language-based "analytic revolution" in philosophy (or "linguistic turn" as Rorty opined) which arose in the US and England facilitated the "new" philosophy of education in the 1960s (e.g., Scheffler and R.S. Peters, respectively).

The "analytic school" in education had sought to improve teacher professionalism by augmenting the usual study of the "doctrines of the great educators" with added philosophical analytical skills to help sort out educational language and thinking (which they had diagnosed as incredibly confused). They also sought to combine their reform effort with guidance sought from research in the social sciences. It allowed for neat separation between the roles of philosopher and scientist, a dualism between theory and practice, and essentially pictured *educational theory as applied science* (a view Piaget held into the 1970s). Needless to say, the "post-analytic revolt" which came afterwards challenged and rejected many of the previous guiding views and assumptions, including its dualism, its epistemological objectivism and deficient language theory, and its philosophy of science (the so-called received view).

In its wake diverse, contemporary "schools of thought" (Barrow 2010) have championed various anti-theory, anti-foundationalist and assorted postmodernist, constructivist, and sociopolitical views. These in turn certainly suffer problems of their own (not to be appraised here), suffice to note others have recently come to reprieve the status of theory.[67] Its proponents not only take issue with anti-theory and postmodern-type arguments but also equally with previous analytic inspired views and dismiss the secondary reliance of educational theory on the social sciences, or worse, its reduction to a mere branch of the field (Carr 2010; Egan 1983, 2002, 2005).[68] They have reasserted the worth of philosophy to deliberate upon educational theory independent from constraints they see placed upon it, especially from scientific psychology.[69] They advocate in spirit that philosophy of education should once again claim its own unique, rightful place, neither accepting subordi-

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[67] So that it may "engage in explorations of what [science] education might be or might become: a task which grows more compelling as the 'politics of the obvious' grow more oppressive. This is the kind of thing that Plato, Rousseau and Dewey are engaged in on a grand scale" (Blake et al. 2003, p. 15).

[68] Carr holds that educational theory might be better suited to ethics (moral reasoning) than with any sort of empirical science, which is not to dismiss the worth of some empirical work: "On closer scrutiny, it seems that many modern social scientific theories of some educational influence are often little more than normative or moral accounts in thin empirical disguise" (2010, pp. 51–2). This deduction leaves unanswered the important question as to what the proper role and value of empirical research for educational theorizing is to be. The topic is controversial and engenders debate in PE. See Egan (2002) and Hyslop-Margison and Naseem (2007) for a negative assessment and Phillips (2005, 2007, 2009) for a positive view.

[69] "We have suffered from tenuous inferences drawn from insecure psychological theories for generations now, without obvious benefit" (Egan 2002, pp. 100–101).

nate status nor intending to displace the social sciences, rather seeking complimentary standing.

On a related issue, because "theory" is often ill-defined in education (Thomas 1997) and usually strictly identified with learning theory in science education (e.g., Norris and Kvernbekk 1997), one needs to distinguish this term from "grand theory" or *metatheory*—the sort of thing Plato, Rousseau, and Dewey were concerned with (Schulz 2009a).[70] The original emphasis on the requirement for a metatheory in education had been discussed by Aldridge and associates (1992) following the proposal first put forth by Egan in the early 1980s encompassing his critique of "scientific psychology" and the demand educational studies stake out independent territory (Egan 1983). Such a theory could very well insist on the difference between psychological and educational development. *The essential merit of metatheory lies in creating curricular coherence, properly transposing subject content knowledge for the learner, and steering educational aims.*

Any educational metatheory must need be a normative one, for it seeks to *prescribe* an educational process to ultimately yield a certain outcome or *aim* (Hirst 1966). This is usually a kind of person or the ideal of what an educated individual should aspire to become given the values and dispositions to be cultivated and methods employed in the specified program (Frankena 1965). Further, it is in the worth of that final aim that the pedagogical methods of the educational project are justified, which traditionally have themselves been framed within the values and aspirations a society has deemed of ultimate importance: "The *value* of this end-product *justifies* the stages that lead towards its realization. Becoming a Spartan warrior justifies training in physical hardship. Becoming a Christian gentleman justifies exercise in patience and humility" (Egan 1983, p. 9; original italics).

In Western civilization a succession of diverse aims or ideals have historically followed since the time of Ancient Greece, and some of the greatest Western minds have been preoccupied with formulating various philosophies of education to define their respective ideal and suggest ways to realize it (Lucas 1972): Plato, the (philosopher-king) man of knowledge; Aristotle, the "good" or "happy" active citizen; Augustine and Aquinas, the Christian saint; Locke, the successful Christian mercantile gentleman; Rousseau and romanticism, the natural development of self-actualization; Kant, the autonomous individual, self-ruled by moral "good will"; and Dewey, personal and social "growth" through ever-changing experience, as the basis for democratic living.[71]

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[70] Phillips (2002, p. 233) terms these "classic theories of teaching and learning."

[71] It should be noted that Dewey's aim is among the least predetermined of the others, although it could reasonably be argued that Kant's ideal is also dynamic insofar as he allows for education's dual aim, the "perfecting" of man *qua* man plus the improvement of society and "the human race." In addition, Frankena (1965, p. 156) also notes that such a dual aim in Dewey could considerably conflict—that the expected growth of the individual and society may clash—in anticipation of Egan's critique, which claims the clash is inevitable insofar as modern schooling is molded according to progressivist precepts. Alternatively, for Dewey, but also for Aristotle and Kant, such a possible conflict was thought to be reconcilable in principle.

Frankena (1965) insists any philosophy of education must ask itself three basic questions: *what* dispositions (or "excellences") to cultivate, *how* to cultivate them, and *why*?[72] When examining the position of the educational theorist Kieran Egan (1983), he seems to have these same in mind but reformulates and generalizes them with a slight shift in accent. Instead of using terms like "dispositions to be cultivated" and "ideal," he talks in terms of "end product" and "aims" while explicitly raising the important fourth component of *development*—it is of the essence of an educational *metatheory*, he writes, that it answers four key questions: what to teach (curriculum), how to teach (instruction), when to teach it (stages of learner development), and most importantly, why to teach it (specification of the end product, aim, or ideal). That said, the similarity in questions and intent is obvious.

Egan (1997) has further argued that *three* long-standing yet venerable and operative *ideas* in education (themselves inexorably embedded within science education) are undermining each other.[73] Schools in the West as educational projects are ineffectual primarily because they are caught between three chief objectives (or rationales) which successfully serve to check or undercut each others' intended aims: whether to teach science for (1) intellectual development (knowledge), or (2) for individual fulfillment (character), or (3) for socioeconomic benefit. (The first can be associated with the original knowledge-based educational project of Plato, the second with Rousseau, and the last is a cross-cultural and timeless expectation of most societies.)[74]

39.5.1.1 Educational Metatheory and Scientific Literacy

When science educational goals are examined historically, these three are ubiquitous; they persistently present themselves albeit in different guises, and they certainly can be identified throughout science educational reform history (Bybee and

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[72] Such questions are actually the purview of what is demanded of an educational *theory*. Philosophy of education properly understood is a much broader field of inquiry that encompasses an analysis of such theories and questions (Peters 1966), which today usually overlaps with curriculum studies. Frankena seems to have been working with a constricted conception solely at the level of theory.

[73] Smeyers (1994) identifies the same quandary for Western European education.

[74] In brief, socialization conflicts with the "Platonic" (knowledge-focused) project because the former seeks the conformity to values and beliefs of society while the latter encourages the questioning of these; socialization also conflicts with the "Rousseauian project" since the latter argues that personal growth must conflict with social norms and needs. It sees growth and hence education in *intrinsic* terms instead of as utility for other socially defined ends. (Here exists the principal tension between the *Bildung* tradition and the dominating utility view of education and science literacy of the English-speaking world.) The Platonic and Rousseauian projects conflict because the former assumes an epistemological model of learning and development and the latter a psychological one. In the former "mind" is created and the aim is *knowledge*; in the latter it develops naturally, requiring only proper guidance, and the aim is *self-actualization*.

DeBoer 1994).[75] Considering the current controversies about prioritizing goals in science education, one may be surprised to learn that even educational debates have a long history. Once again, PE can offer insight into long-standing science educational dilemmas. Aristotle records:

> But we must not forget the question of what that education is to be, and how one ought to be educated. For in modern times there are opposing views about the task to be set, for there are no generally accepted assumptions about what the young should learn, either for virtue or for the best life; nor yet is it clear whether their education ought to be conducted with more concern for the intellect than for the character of the soul. (Aristotle, *Politics*, VIII ii: 1337a33; 1962/1981, p. 453)

It is remarkable to contemplate how his discussion mirrors the debate of values and aims that has steered science education since its inception in the nineteenth century. Consider if you will the conflicting meanings (post-WW2) of "science literacy,"[76] still identified as the overall objective of science education as discipline and practice: whether it is to be primarily understood as personal self-fulfillment (i.e., "virtue" as its own intrinsic worth) or for "critical citizenship" in a democracy (i.e., as instrumental worth; "the best life": STS), or rather solely for development of "mind" per se, as mastery of subject-based formal knowledge and as a tool for developing inductive (later redefined as "critical") reasoning (i.e., "intellect" development; science "processes": traditionalism; "scientific argumentation"). Lastly, whether it should encompass foremost moral development when arguing "socioscientific issues" (SSI) or "science education as/for sociopolitical activism" (i.e., "character of the soul"—always seen by Aristotle in terms of sociopolitical *activity*).

Note as well that the three fundamental goals underlying education (as elaborated above) can be identified here and mapped onto the corresponding conceptions of literacy and onto existing school science educational paradigms.[77] Some critical

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[75] No one normally holds exclusively to one or the other, although usually one or the other is emphasized over the other two at a given time (depending upon the defined "crisis" at hand and under influence of respective social group interests), and the modern school and indeed many "standards" documents aim at a sort of *balance* between them. Roberts (1988), too, holds that "balance" is both desirable and achievable during public policy curriculum deliberations. Egan though insists that the attempts to achieve "balance" are illusory and must undermine the strengths of any one at the cost of the others.

[76] The term itself first came into use in the late 1950s. Initially broadly framed in terms of science, culture, and society relationships, it soon came however to mean learning technical, subject-specific knowledge: "This emphasis on disciplinary knowledge, separated from its everyday applications and intended to meet a perceived national need, marked a significant shift in science education in the post-war years. The broad study of science as a cultural force in preparation for informed and intelligent participation in a democratic society lost ground in the 1950s and 1960s to more sharply stated and more immediate practical aims" (DeBoer 2000, p. 588). By the 1980s the phrase had become commonplace: "Yet despite the problems of definition, by the 1980s scientific literacy had become the catchword of the science education community and the centerpiece of virtually all commission reports deploring the supposed sad state of science education" (Shamos 1995, p. 85).

[77] As can the seven "curriculum emphases" behind science curricula, identified by Roberts (1988)

observers had thus come to the conclusion that already by the late 1980s, the usefulness of the literacy concept had exhausted itself.[78] *We have a situation here where a discipline cannot agree on the most fundamental purpose and goal of its educational endeavor.*

One can therefore conclude, given this consistent mode of discourse about "science literacy," that the community is placed before one of *three* choices:

(i) *Exclusivist* option: one chooses either an already given or hoped for curricular paradigm; this could be the knowledge-based, specialist "vision I" literacy conception (the given: traditionalism) or, at the other end of the spectrum, opting for an "extreme" form of "vision II" (as Roberts (2007, p. 769) remarks), by redefining literacy as "collective praxis"—such as the (hoped for) image held by Roth and Barton (2004).

(ii) *Inclusivist* option: one agrees instead to hold fast to as many conflicting meanings as possible (e.g., Hodson 2009). Along with DeBoer (2000), one simply accepts the term stands for "a broad and functional understanding of science for general education purposes" (p. 594), and "because its parameters are so broad, there is no way to say when it has been achieved. There can be no test of scientific literacy because there is no body of knowledge that can legitimately define it. To create one is to create an illusion" (p. 597). Rather, only specific goals can be achieved in a piecemeal fashion, where his historically identified *nine* different conceptions are chosen as in a smorgasbord, attentive to the context of school culture and society wishes, and where "schools and teachers need to set their priorities" (ibid.). With this option, divergence is chosen. It is then assumed that "consensus about one definition throughout the worldwide science education community is a goal not worth chasing" (Roberts 2007, p. 736).[79]

(iii) *Abandonment* option: one chooses to reject the term as both useless and meaningless for educational purposes, along with Shamos (1995) and Solomon (1999).

In any case, if an educational metatheory is to be of service to science education, it must also acknowledge and address these options in the deadlock.[80] It may also

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[78] Shamos has insightfully argued that its common conception tied to citizenship is fundamentally flawed, that the community is chasing a utopia, that it continues to refuse to accept the grounds why it has failed in achieving it, and finally that many rationales typically put forth to justify it are a *myth.*

[79] Option two although seemingly attractive on the surface does not seem viable, and one can imagine numerous problems associated with it. Just mentioning one, it assumes a degree of autonomy for schools and teachers which they generally lack and which in the climate of "accountability" and standardized testing and under the influence of powerful outside social groups would seem to check their ability to make the kind of choices DeBoer would like. A reversion to option one would in all likelihood result, namely, the default traditionalist position.

[80] A series of papers presented at a recent conference attempting to articulate "a more expansive notion of scientific literacy" illustrate the problems associated with this deadlock once more and why the sought-after solutions remain so elusive; discussions including educational theory and philosophy are conspicuously absent (Linder et al. 2007).

put into question the assumptions and scope of the discussion and even the entire character of the discourse which has heretofore been conducted (Schulz 2009b, 2011; Witz 2000).

39.5.1.2 Educational Metatheory and Advance of Science Education as a Research Field

Fensham's *Identity* book (2004), interestingly enough, also offers an important look at the role of theory (Ch.7) within the science education research community. He admits that the development of theory is a significant indicator of a discipline's advance as a research field:

> If the existence of theory and its development is a hallmark of a mature research field there is some evidence that the research in which the respondents have been engaged in science education has reached this point. On the other hand, the role that theory plays in the respondent's remarks was so variable that it is not possible to attach this hallmark in a simple way to much of their research. (Fensham 2004, p. 101)

With that admission he acknowledges that the usage of theory is restricted and there was little interest on the part of researchers to develop their theory of choice further. What is significant though is the range of *borrowed* theories from outside research fields that the researchers have heavily relied upon.[81] The spectrum stretches from social anthropology, ethnology, and cultural theory to psychology, cognitive science (e.g., information processing; schema restructuring), and philosophy of science (e.g., conceptual change theory).[82] He notes those researchers employing a "political framework" to curriculum, or concepts of power and ideology, shift the common focus of science education onto entirely different factors that influence science teaching and learning. Essential PE-type questions like "what counts as science education?" or "how are ideological meanings reproduced in science education?" are raised, but surprisingly not addressed with that perspective or discipline in mind. One observes rather that in all cases educational theory and philosophy of education nowhere make an appearance.

To the point of the subject at hand, Fensham does mention the topic of "grand theory" (p. 107). He writes that only *one* respondent had admitted to theorizing on this scale, namely, the biologist and educator Joseph Novak, who had earlier published *The Theory of Education* (1977).[83] Novak has today continued to hold, as

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[81] "This borrowing can have the healthy effect of bringing new insights to bear on the problems of science education, but it can also lead to superficial descriptions that do not seem to be pushing for deeper understanding" (2004, p. 101). He fails to mention a *third* possibility that outside theories can do outright damage to education, as Egan (1983, 2002) argues for the cases of behaviorism, Piaget, and progressivism. The presumed relevance of cognitive science has lately come into question as well (Slezak 2007).

[82] Reliance upon psychology is clearly predominant, primarily Bruner, Gagne, and Piaget in the 1960s and 1970s and the significant role they played marking the revolt against behaviorism.

[83] This book, however, as is familiar today, is based on the psychologist Ausubel's quasi-neural theory of meaningful learning in combination with Toulmin's philosophy of science and principally restricted to learning theory.

Fensham comments, to the value of this theory and the belief that "theories in science education would be developed that have predictive and explanatory power, just as theories in the natural sciences have" (p. 106). This belief closely aligns educational theory with empirical theories in the natural or social sciences,[84] an arrangement both Hirst (1966) and Egan (1983, 2002) explicitly reject.

39.5.1.3 Educational Philosophy and Science Education as "Sociopolitical Activism"

One contemporary reform movement (spearheaded by some international researchers and popular with some policy advocates), namely, "science education as/for sociopolitical action," has been articulated with intentional philosophical perspectives. It could reasonably be interpreted as a rudimentary sort of "*philosophy of*" science education (PSE) as here elucidated (though granted, not formulated in this fashion). The position that science education *should* be oriented (if not exclusively so) to perform sociopolitical action is a normative claim argued on philosophical grounds, justified because of the apparent promise/claim of enhancing critical-minded citizenship and forwarding democracy. It patently stipulates categorical answers to the key questions: "What counts as scientific literacy?" "What counts as science education?" "What is it for?" Whether or not such a muscular and singularly focused PSE can do justice to the other historically identified aims associated as central to science education (including the *aesthetic* component of science; DeBoer 2000; Girod 2007), and therefore the best option for policy deliberations and reform, is a matter for some dispute—although a considered debate especially one involving philosophy of education (PE) is surprisingly lacking to date.[85]

That this sort of politicized PSE represents a "radical program" to challenge common school science education is understood (Jenkins 2009; Levinson 2010). Here our focus is to ask: is such a "program" an adequate PSE?[86] Science education, for example, could plausibly "do" sociopolitical action at times while rejecting "as" and "for." In any event, does politico-social activism as put forth substitute ideology

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[84] It is admitted that Novak's writings offered an important counter-theory in support of the growing dissatisfaction with the dominance of Piagetian theory arising in the late 1970s (although some science educators continue to hold neo-Piagetian views). With the growth of conceptual change and constructivist research in the 1980s and the influence of Kuhnian philosophy-of-science, this dominance was gradually displaced in the research community. On the other hand, Erickson (2000) cautions there is much common ground between Piaget and the newer constructivist theories. Egan's cultural-linguistic metatheory (1997) is inclusive of learning theory but goes beyond it and outright rejects Piaget (Schulz 2009b).

[85] Leaving aside questions if its individual educational claims are either warranted or empirically validated. Strong advocates for this kind of politico-social activist PSE (just naming some researchers) are Hodson (2009) and Roth and Desautels (2002). Criticisms leveled against it are provided by Hadzigeorgiou (2008) and Levinson (2010).

[86] Does it fully take into consideration the three dimensions of the synoptic framework shown in Fig. 39.1?

for philosophy?[87] Does it presuppose educational metatheory? The present author would argue it must (although this feature is seldom articulated; i.e., social reconstruction). Stepping back, must *any* methodical PSE presuppose metatheory (of some kind)—or can it be gone around for, say, a list of rationales, principles, and exhortations? That debate has not yet begun, but would be welcomed.[88]

One of the responsibilities of a philosophy of science education (PSE) at the research level would be to expose educational theories (especially metatheories), as well as better clarify the relationships between such theories in PE and theories in other (empirical) disciplines (as to their nature, value, and limits), whether one of independence or interdependence.[89] In other words, a philosophical appraisal of several domains, such as conceptual clarification and the validity of borrowed ideas; scrutiny of epistemic and/or moral and political aims—their character and prioritization; analysis of the theory-practice dilemma; also the character, quality, and significance of kinds of assessments or tests employed (range of usefulness), etc.; and hence the question of boundaries, applicability, and relevance.

39.5.2 Epistemology, Knowledge, Understanding, and Hermeneutics

39.5.2.1 Epistemology, Belief, and Epistemic Aims

That science instructors and their technical textbooks are so concerned with accurate and exhaustive transmission of canonical scientific knowledge clearly reveals the central significance of epistemology to science education.[90] One can identify this preoccupation of academic sciences courses (a chief aim of school and college science) with the constricted and popular rendition of the customary *knowledge aim*.

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[87] Roberts (1988, p. 50) had earlier cautioned the research community about the "*individual ideological preference* of professors of science education" which can "indoctrinate science teachers into believing that what counts as science education is the ideology of a single curriculum emphasis (or perhaps a few emphases)" (original italics).

[88] It seeks as well to address the common blurring of lines between "descriptive" and "normative" research work, the expectation *that* classroom research *should* change classroom teaching and learning, as Sherman (2005) points out, but strictly in accordance with a specified (ideological) program. This academic conflation may indeed be due to our culturally inherited situation, i.e., "if we can't be objective, we'll be openly ideological" (p. 205), but regrettably real "openness" is rare. The argument here in a nutshell is that science education avoids (c)overt ideology for candid philosophy.

[89] Such a conversation can be considered an extension of one already discussing the difference between epistemology and psychology (Duschl et al. 1990; Matthews 2000; Southerland et al. 2001) or critiquing the assumed validity of cognitive science theories for science education (Slezak 2007).

[90] For some time a major portion of science education research has in fact been focused on analyzing and critiquing the strengths and weaknesses of school science epistemology, whether of subject content, or of the student, or of the teacher.

Here is another area where PE discourse can provide relevance, for the knowledge aim or truth aim has been fundamental in the traditional view of education, including its *liberal* construal—notwithstanding significant attacks on that objective from different educational perspectives (e.g., progressivism, post-analytic, postmodernist).

> Although transmitting knowledge is not the only aim of education, it is surprisingly substantial in its ramifications. Because we can compare various educational practices to determine which ones better advance students' knowledge, the knowledge-aim offers educational guidance, justifies central educational practices, and exposes complexities in the educational policies it supports. (Adler 2002, p. 285)

Science teachers plainly assume their courses or textbooks provide (technical) knowledge, indeed substantially *true* knowledge—and for the most part, they would be correct (e.g., propositional knowledge of final form science; Duschl 1990).[91] Yet being philosophically inclined means giving pause to reflect on what *basis* this can be claimed (expertise of the authors? Authority of the scientific community?). HPSS-based reforms do insist, of course, that *content knowledge* (CK, of teacher or curriculum) requires expansion and corrections (e.g., historical and epistemological *context* to be properly understood and learned).[92] But stepping back and asking about justifying CK, or "what is knowledge?"[93], is to venture into both philosophy (P) and PE territory (the right segment of the triangle in Fig. 39.1). The kinds of answers to these questions have vital educational ramifications. How, for example, can one justify teaching evolutionary theory if its stake in knowledge and truth cannot be established against intelligent design claims? Or taking the "culture wars" into view, is cultural indigenous knowledge of nature *true* scientific knowledge? Are there other kinds? If so, how are they legitimated? How to best distinguish them from science?[94]

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[91] This has also been referred to in the research literature as the "disciplinary view of knowledge" in contrast to "personal learner epistemology" and "social practice views of epistemology" (Kelly et al. 2012). The latter defers to science studies research and how knowledge is attained and justified through discourse practices within epistemic cultures (Knorr Cetina 1999). What is significant is that "within this perspective, knowledge is seen as competent action in a situation rather than as a correct, static representation of the world" (p. 286). What is not being acknowledged is that the two stated perspectives are themselves beholden to two different epistemological philosophies, namely, pragmatism and objectivism. While science education has traditionally been in the thrall of the second and is now expected to shift to the first, it could better take advantage of the respective benefits of each.

[92] Even when basic science "subject matter" is taught, it is always accompanied by some context that may operate covertly (e.g., preparatory, socio-utility, etc.). Such contexts have been called "meta-lessons" (Schwab), "curriculum emphases" (Roberts 1988), and "companion meanings" (Roberts and Oestman 1998).

[93] Also, what kind of science knowledge is of *most* worth (a key question of prioritizing subject content)?

[94] A very informative discussion on such questions, including examining beliefs, learning, knowledge, and critical inquiry pertaining to the aims of science education, can be found in Nola and Irzik (2005). The comments which follow can be considered supplemental to their work.

Students, when not just assuming the authority of the textbook or teacher, occasionally wish to have explained to them the grounds for knowing, grounds that can only partially be established when "doing science" (i.e., scientific inquiry). Four possible harmful *dispositions* to knowledge students can develop from science classrooms are cynicism, dogmatism, skepticism, and relativism, and Norris (1984) rightfully asks "can all these be avoided?" Teachers require philosophical intelligence not just for telling these apart, but awareness when they crop up during instruction and for strategies to overcome them.[95] Thankfully there already exists a tradition in PE that can assist them, which has sought to demonstrate the relevance of epistemology for education (Adler 2002; Carr 1998, 2009; Siegel 1988).

The standard account of knowledge is "justified true belief" (JTB), which stipulates three conditions in order for someone to say they "know X." For instance, science educators would not be satisfied if a student stated they "know" the Earth orbits the Sun but could not provide any evidence for this proposition. In this case the student has a *true belief* (two conditions met), but without justification could not be said to have attained knowledge. Even if philosophers have brought forth serious challenges to JTB[96], this doctrine of traditional epistemology still retains its value in assisting science teachers' thinking about the differences between knowledge, belief, and justifying conditions in the classroom as they arise (Southerland et al. 2001). It highlights the drawbacks of traditional instruction which can overstress the value of rote learning, algorithmic problem solving, and decontextualized subject content, especially if tied to a policy of exaggerated standardized testing (Hofer and Pintrich 1997; Mercan 2012).

JTB can equally shed light on other cases which can occur where knowledge and belief appear conflated, such as when a student has learned content but refuses to believe it (e.g., "I understand evolution, but I don't believe it"; "I can explain the Bohr model but don't believe atoms exist"). Southerland and associates (2001) have provided an overview of the differing conceptions and occasional clashing views concerning how "knowledge" and "belief" are employed as terms in the separate research fields of philosophy, educational psychology, and science education. They also raise the important pedagogical question whether science education should limit its aim to providing knowledge (or understanding) and not demand changing student beliefs (as required by conceptual change research). An interesting exchange of views between Smith and Siegel (2004) and Cobern (2000, 2004) on this topic illuminates that science teachers need to sort out not just their own presuppositions about knowledge and beliefs but require sensitivity to historical and cultural dimensions of these concepts while attending to philosophical arguments.

Within the field of science education research, Norris (1995, 1997) has analyzed how the JTB view of knowledge finds expression in the aim of *intellectual independence*, one key content-transcendent goal articulated since Dewey and progressivism.

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[95] Certainly the relatively recent research studies to enhance *scientific argumentation* in the classroom also aim towards resolution of the issues and questions raised here, but are not of present concern.

[96] These will not be discussed here; instead see Siegel (2010) and Norris (1997).

He identifies several serious shortcomings of past and recent formulations of this goal (e.g., as found in constructivism and notions of scientific literacy). Norris notes especially the philosophical controversy surrounding the question to what extent, if any, non-experts can reason independently of experts' knowledge and community—hence, to what extent they can be justified to trust in authority and yield to scientists' judgments (and by association, their textbooks). The outcome of the dispute remains contested, but it appears some reliance is indeed unavoidable.

The degree to which intellectual independence is attainable (or not) has major ramifications for the character and educational aims of science education reform movements (like STS, SSI, HPS, social action). It could impose severe limitations, depending upon the stipulated objectives and overall ambition they desire to advance for the discipline, notably which independence-based goals they mistakenly assume school students can rightfully achieve.[97]

Returning to a previous point, Smith and Siegel (2004) in their paper had also named *understanding*—along with knowledge, and *not* (changing) belief—as primary goals for science instruction. The focus here though is not to address their position nor the dispute with Cobern (but noting its significance) rather to point out that "understanding" as both concept and goal has been largely overlooked in the research literature. Its merit with respect to epistemology and the traditional preoccupation with "knowledge" yields a checkered history, too (Toulmin 1972).[98] Yet its prominence does come to the fore in *philosophical hermeneutics* (Gadamer 1976, 1960) as well as Egan's educational metatheory. A systematic investigation of "understanding," its contrast to knowledge, and its merit for science education has yet to be presented.[99]

One fertile perspective on "understanding" has been provided by the late physicist and philosopher Martin Eger (1992, 1993a, b). He had insightfully shown the relevance of Gadamer's "philosophy of the humanities" for science education with regard to the *interpretation* of nature but especially of science *texts*. Hermeneutics, an age-old scholarly discipline, ties understanding to the ability to achieve personal meaning when interpreting text (utilizing the "hermeneutical circle" method). The significance of his ideas lies in offering an alternative approach to viewing science learning and knowing, drawing science education away from psychological and cognitive science perspectives and towards philosophy and the humanities (Bontekoe 1996; Donnelly 2001; Gallagher 1992). Today his ideas are finding useful expression in some research work (Borda 2007; Kalman 2011). He explicitly shifts the emphasis away from epistemology towards *ontology*, away from "knowing" in the

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[97] Kuhn (1970) was skeptical about what science education could achieve in terms of developing independent thought and argued instead the conservative view of reinforcing the conventional paradigm—in part because this furthered "progress" and in part because students had no competence to do otherwise. Schwab held a different view and thought students could be educated to become "fluid inquirers" within and about a discipline. Siegel (1978) has admirably contrasted the two opposing positions.

[98] Mason's (2003) "*Understanding* understanding" is one of the few to explore the contrast.

[99] Some researchers have ventured into this territory; see, for example, Wallace and Louden (2003).

objectivist sense to interpreting, meaning, and being. This shift, or "interpretative turn" (Hiley et al. 1991), has not been entirely endorsed as regards questions surrounding the nature of language, ontology, and the relationship between epistemology and hermeneutics. The next section provides science educators with an unconventional but updated outlook regarding these major topics.

39.5.2.2 Epistemology and/Versus Hermeneutics

Any discussion involving philosophical hermeneutics recognizes two current state of affairs, namely, the ongoing unresolved dispute over the self-conception of philosophy and the so-called interpretative turn from epistemology *to* hermeneutics.

To the first, one identifies that the modern Anglo-analytic philosophical tradition has fractured into two differing schools of thought as to what the nature and role of modern philosophy *is* and can accomplish (represented by the opposing views of Dummett and Rorty; Bernstein 1983). This opposition is reflected as well in contrasting perspectives on language theory—which Charles Taylor has characterized as the *designative* and *expressive* traditions (Medina 2005, p. 39). That said, authors like Bernstein, Rorty, and Taylor nonetheless all comment on the convergence of thinking in both the Anglo-American and Continental traditions which reject *foundationalism* or the former project of grounding philosophy, knowledge, and language ("objectivism"), as Descartes, Kant, Russell, and the early Wittgenstein sought but failed to do.

With the current preoccupation of repudiating this formerly eminent epistemological tradition[100], the task of "overcoming epistemology" has come to mean different things to different thinkers (Baynes et al. 1987). Dewey and Bentley (1949), for instance, sought to overcome subject/object dualism with his pragmatic focus on "transaction," the active/practical behavior taking place between the knower and known. Taylor (1987) correctly views both Quine and Rorty as abandoning foundationalism (with the former attempting to "naturalize" epistemology), while he solely targets overcoming the conception of knowledge as *representation* that lies behind the ambition of the foundationalist project since Descartes:[101] "If I had to sum up this understanding in a single formula, it would be that knowledge is to be seen as correct representation of an independent reality.

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[100] "Current attitudes toward foundationalism, as they have been since Descartes, are sharply divided. The minoritarian conviction (Chisholm, Apel, Habermas, Haack, Swinburne, and others) that some version of foundationalism is or is at least potentially viable is outweighed by the majoritarian belief that in the debate since Descartes, foundationalism has died a natural death and cannot be revived" (Rockmore 2004, p. 56).

[101] Rorty, of course, also surfaces representation, but he explicitly ties it to philosophy as a profession whose role as a foundational discipline (with its "theory of knowledge" being essentially a "general theory of representation") was to adjudicate all cultural knowledge claims, eventually including scientific ones. His view is comparable to Taylor's "To know is to represent accurately what is outside the mind; so to understand the possibility and the nature of knowledge is to understand the way in which the mind is able to construct such representation" (1979, p. 3).

In its original form it saw knowledge as the inner depiction of an outer reality" (p. 466).[102] One notes representation plays a significant role in science and science education, and Giere (1999) argues, in contrast, for its continued importance in science independent of foundationalism. Indeed, some philosophers and science educators have argued for a "fallibilist epistemology" as a viable alternative to opposing foundationalist and radical constructivist views of knowledge and belief (Siegel 2001, 2010; Southerland et al. 2001). The collection of papers in Carr (1998) intends to help guide curriculum policy beyond "rational foundationalism" and "promiscuous postmodernism." The discussions in these works can contribute to advancing teachers' epistemological conceptions and deliberations, whether concerning science, curriculum, or student learning.

The second aspect, as mentioned, acknowledges an "interpretative turn" to have taken place not only in philosophy (due initially to Heidegger 1977) but in the natural and social sciences as well (inclusive of language theory)—though granted, still subject to much dispute—that also seeks to move "beyond objectivism and relativism" (according to Bernstein 1983).[103] Such a move can be considered a shift in the philosophical emphasis entirely "from epistemology to hermeneutics," as both Rorty and Gadamer have claimed[104]; certainly it can be admitted the relation between the two modes of inquiry is contentious and differing conceptions of language inform both.

Furthermore, although there are many similarities in Rorty's and Gadamer's positions, there exist important differences as well as to the nature and task of epistemology and hermeneutics, which is instructive. For example, while Rorty would agree that Anglo-analytic philosophy of language has slowly come to abandon the notion of language as correct "picture of the world"[105], he would disagree with Gadamer's universalist perspective of philosophical hermeneutics (with its inherent view of language as the *medium* of all understanding). Both agree that hermeneutics is not to be considered a successor to epistemology, rather that it involves an entirely different approach to comprehend the world—indeed Rorty construes it as a kind of "paradigm shift" (one that is holistic, historicist, and pragmatic). While Rorty makes

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[102] Taylor links the success of "knowledge as correct representation" standpoint with two factors: its link with the rise of mechanistic science in the seventeenth century, whose mechanized worldview overthrew the Aristotelean one with its notion of "knowledge as participation" ("being informed by the same *eidos*, the mind participated in the being of the known object, rather than simply depicting it," p. 467); secondly, the influence of Cartesian philosophy that insisted a new reliable "method" was required that could guarantee certainty of the representation. Yet this method entailed, unlike in philosophical antiquity, the reflective and critical cast of individual *mind* performing a subjectivist inward turn. Rorty's view is similar (1979, p. 248).

[103] He cites such authors as Rorty and Taylor (in philosophy), Gadamer (in language theory), and Kuhn and Hesse (in philosophy of science). Other philosophers of science endorsing hermeneutics are Heelan (1991) and Ihde (1998).

[104] See especially Rorty (1979, Chap. 7) and Gadamer (1989, p. 235).

[105] "Putnam now agrees with Goodman and Wittgenstein: to think of language as a picture of the world—a set of representations which philosophy needs to exhibit as standing in some sort of nonintentional relation to what they represent—is *not* useful in explaining how language is learned or understood" (1979, p. 295; original italics).

a sharp distinction between the two but sees them as complementary and mutually supportive (epistemology for "normal discourse" and hermeneutics for "abnormal"), Gadamer views them rather as antagonists: hermeneutics as the universal condition of understanding (and hence of *being; Dasein*)[106] but epistemology as a failed *epistéme*-based, historico-philosophical venture whose time has come and gone. The project has died and should be buried. Rorty correctly stresses that Gadamer had emphasized *Bildung* as historical enculturation (hence the crucial role of education) as a proper goal of hermeneutics—construed as an open project of how understanding takes place through interpretation and dialogue, a form of *intersubjectivity.* This is seen in contrast to "knowledge" possession and obsession of isolated, individual cognition (the foundationalist project), but he would not consent that such "understanding" entails knowledge. Rorty is clear that "knowledge" is fallible and constrained to the "normal discourse" of a particular (historical) sociocultural paradigm (explicitly referencing Kuhn's ideas).[107] But taking such a position on a *standard* of knowledge one can argue, alternatively, must implicate Rorty's outlook as committed to the epistemic assumptions of Cartesian foundationalism.[108]

There is certainly more that can be surveyed here in the debate about the shift "from epistemology to hermeneutics." Siegel (2010), for instance, takes issue with Taylor's arguments for "overcoming" epistemology, while Suchting (1995) criticizes many of the "lessons" supposedly drawn from hermeneutics. Several very important questions exist that still need addressing, such as if the common division between *explanation* and *understanding* is abandoned—which has long been accepted as *the* major difference between the natural and social sciences (Mason 2003)—and "interpretation" comes to characterize all human inquiry, does or should a "contrast class" exist in opposition to it? Thereto, how can or should one demarcate the lines between the humanities and the different sciences? Moreover, how does one adjudicate between better and worse interpretations? Is hermeneutics[109] really an alternative

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[106] This hermeneutic perspective on learning and understanding corresponds with the newer epistemological perspectives of the field: "… increasingly, science education researchers are viewing meaning as public, interpreted by participants (and analysts) through interaction of people via discourse including signs, symbols, models, and ways of being" (Kelly et al. 2012, p. 288).

[107] Hence his complaint that one can distinguish between "systematizers" (those engrossed in normal discourse) and "edifying" philosophers (anti-foundationalists like Dewey and hermeneutic thinkers like Heidegger, Gadamer, who disrupt it) within the tradition—the latter whose status as "true" philosophers is often questioned by academic professionals.

[108] Rockmore (2004, p. 57) writes that Rorty maintains "a strict but wholly arbitrary distinction between epistemology and hermeneutics in order to equate the failure of foundationalism with a form of skepticism that cannot be alleviated through a hermeneutical turn." He accuses Rorty of still clinging to a standard of knowledge that he admits cannot be met. Rorty freely concludes that one can no longer hope to bring the mind in contact with the real and that *interpretation* must be the alternative, but just denies this will lead to knowledge in the conventional sense. Alternatively, Rockmore argues that "the main strategy for knowledge is, and always has been, interpretation" (ibid), not to be taken as tantamount to skepticism.

[109] This is not meant to imply this field of study is monolithic, and commentators commonly distinguish between "right-wing" (Gadamer) and "left-wing" (Derrida) factions. Yet such a categorization

paradigm to epistemology (as Gadamer and Rorty insist) or another albeit extraordinary version of epistemology itself, just not of the classical foundationalist sort (as Rockmore (2004) and Westphal (1999) contend)?[110]

There are fundamental issues and concerns identified here that a philosophy of science education (PSE) would equally need to consider and evaluate, which have necessarily arisen in the dispute between the advocates of epistemology, hermeneutics, and their different perspectives on language, knowing, and understanding.

39.6 Conclusion

Philosophy and philosophy of education continue to remain outside the mainstream of thinking in science education. The chief purpose of this chapter has been to bring them closer into the fold. Philosophy is, on the one hand, underappreciated and ignored by science teachers, on the other, occasionally raided, used, and abused by science education researchers. Philosophy of education by contrast (and when compared to philosophy of science) has the dubious distinction of being disregarded by both groups.

Philosophy as a discipline of critical inquiry enables teachers to develop a thoughtful, critical capacity to reflect upon curricular, epistemological, and popular media issues as they arise, whether during classroom discourse or professional policy deliberations. Philosophy is not far below the surface in any classroom, and in truth cannot be avoided. This holds especially when discussing common terms like “law,” “theory,” and “proof,” or justifying content knowledge, or analyzing national “standards” documents, or providing coherent educational rationales for their courses, or for detecting curricular ideologies and conveyed textbook myths (e.g., academic rationalism, indoctrination into scientism, epistemological positivism, historically defined convergent realism, evolution versus intelligent design arguments, ambiguities and hazards of modern techno-science, cultural and personal bias). Philosophy of education as a subdiscipline prepares a forum of informed analysis and discussion on a range of topics and issues that bear directly on science education as an educational project, which has deep roots in the historico-philosophical past.

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is equally overly simplified. Those in educational studies—see Gallagher (1992)—distinguish four separate schools: conservative (Dilthey; Hirsch), moderate (Gadamer; Ricoeur), radical (Derrida; Foucault), and critical (Habermas; Apel).

[110] Rockmore maintains that the shift leads to a *redefinition* of epistemology, from “knowing the way the mind-independent world is” to “the interpretation of experience” which is justified by the standards in use in a given cognitive domain. In this reformulation “then epistemology as hermeneutics presents itself as a viable successor to the traditional view of epistemology—indeed as the most likely approach at the start of the new century” (p. 11). Westphal criticizes Rorty for failing to distinguish between classical epistemology and hermeneutics seen as a generic epistemological task, hence, to differentiate the replacement of only one type (foundationalism): “*hermeneutics is epistemology,* generically construed … it belongs to the same genus precisely because like them it is a meta-theory about how we should understand the cognitive claims of common sense, of natural and social sciences, and even metaphysics and theology” (p. 416; original italics).

A philosophy of science education (PSE) can be understood as a *synthesis* of (at least) three academic fields of philosophy (P), philosophy of science (PS), and philosophy of education (PE), each of which have distinctive contributions to make in its development. It can be interpreted as a "second-order" reflective capacity on the part of the teacher, as an extension of their pedagogical content knowledge. The research field requires this capacity to think deeper and more systematically about the unique educational dimensions of teaching and learning of science as philosophy, as profession, and as practice. It should be inaugurated as a new *fourth* area of research inquiry.

PSE is ultimately concerned with the explicit *problematizing* of school science and its epistemology for two substantive reasons: (i) to recognize the current inadequate portrayal as inauthentic science and so to improve the content knowledge (CK) of both the curriculum and teacher through HPSS studies and integration and (ii) to allow for the effective didactic transposition of subject content for the culturally rooted, age-appropriate learner in accordance with educational aims, philosophy, and theory.

Pertaining to performing useful functions, its value is taken as being *threefold:* it serves to, first of all, provide a platform for both researchers and practitioners (in their separate ways) to perform meta-analysis (critical function); secondly, to reconceptualize, remake, and reform curriculum and instruction (creative function); and lastly, to implement, as an example, effective critical thinking for teacher and student, appropriate to subject content and age level (pragmatic function). In the process it is understood such a philosophy when developed would be articulating in essence its meaning of "scientific literacy" and thus specifying and prioritizing essential objectives for science education. Whether or not it could successfully perform these functions without an explicit educational metatheory at hand is open to challenge and debate. In any event, it would ultimately aim at improving science education by broadening the research field and opening new territory for exploration, as well as assisting teachers in broadening their theoretical frameworks, sharpening their critical acumen, and enhancing their pedagogical content knowledge.

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Chapter 40
Conceptions of Scientific Literacy: Identifying and Evaluating Their Programmatic Elements

Stephen P. Norris*, **Linda M. Phillips, and David P. Burns**

'Scientific literacy is a programmatic concept' (Norris and Phillips 2009, p. 271). Programmatic concepts have elements that point in a valued direction or name a desired goal. In the case of scientific literacy, it points to goals that educators, scientists, and politicians want for citizens and society. It should not be surprising, then, that scientific literacy is contested. Not everyone possesses the same sense of valued directions and desired goals, so different individuals and groups urge their views on others. The question raised in this chapter is, 'By what means can the programmatic elements of conceptions of scientific literacy be identified and evaluated?'

First, we provide a detailed analysis of the nature of programmatic concepts and provide examples of the programmatic elements found in conceptions of scientific literacy. Given that definitions of scientific literacy bear upon what is taught in science education, a lens is needed through which to identify and judge these programmatic elements. Specifically, what values underlie these elements and what theories of value might be brought to bear in assessing them? The answer to this latter question will compose the second major section of the paper in which we present an analysis of approximately 70 conceptions of scientific literacy found in the literature since the year 2000. We identify the goals that each of these conceptions of scientific literacy implies and uncover the programmatic elements that are used to justify these goals. Our purpose here is not to be exhaustive in presenting

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conceptions of scientific literacy but to present a sufficiently wide range of views to have a good representation of goals and programmatic elements. Third, we point to a number of pitfalls in any attempt to make preferential selections among the programmatic elements of conceptions of scientific literacy.

40.1 Programmatic Concepts

Programmatic concepts are of notable importance in education because of education's practical orientation toward 'social practices and habits of mind' (Scheffler 1960, p. 19). Programmatic concepts 'are not recognizable as such by their linguistic form alone: reference to the context needs to be made' (Scheffler 1960, p. 19). A study of the context in which a concept is used can reveal whether the concept has the effect of implying practical consequences or whether it does not serve such a purpose. Thus, programmatic concepts require 'independent, practical evaluation' (Scheffler 1960, p. 21) because they can raise serious moral and practical issues.

Like any concept in education, we expect programmatic concepts to meet certain linguistic and logical standards such as consistency, suitableness, and non-arbitrariness. However, programmatic concepts carry the extra burden of expressing value choices that embody programmes of action. We thus understand that to evaluate a programmatic concept, such as scientific literacy, it is necessary to consider both its linguistic features and value implications. Thus, an overriding question that we shall consider is, 'What is promised as a result of adopting a particular conception of scientific literacy?' We shall argue that any adoption should follow, rather than precede, the evaluation of what is promised in terms of sound theories of value.

Robert Ennis (1969) claimed that a programmatic concept takes the form of a definition, but 'it is more than this' (p. 178). Ennis's is a key point of focus, because it reminds us that programmatic concepts are not neutral descriptions of usage, compared let us say to dictionary definitions, which are intended objectively to describe linguistic practice. Programmatic concepts are not neutral, because they both imply a programme of what should or ought to be done and support that programme with explicit or implicit terms embedded within the meaning of the concept. According to Ennis, a programmatic concept effectively is 'a proposal (that is, a request, or command, or entreaty, etc.) for adoption of a program or point of view' (p. 179). For example, part of the conception of scientific literacy offered by Millar and Osborne (1998) is that a scientifically literate person has 'sufficient scientific knowledge and understanding to … read simple newspaper articles about science…' (p. 9). In this concept, we can see both of Ennis's elements at work. First, the concept reads like a definition. Thus, we can raise the questions of fact: Is the definition accurate? Is this what people mean by 'scientifically literate person'? Second, the concept reads like a proposal: We should take scientifically literate people to be able to read simple articles about science; we ought not to settle for less. Thus, we can raise the value questions: Is this how we ought to think of scientifically literate people? Should we consider reading simple newspaper articles to be important to scientific literacy? Is being able to read simple newspaper articles about science sufficient? The answers to these questions are not straightforward, but what is important is to acknowledge that these two elements are entailed: the questions of fact and the questions of value.

Consider a concept of our own to see again these two elements working. We theorized a fundamental sense of scientific literacy that 'means comprehending, interpreting, analyzing, and critiquing [scientific] texts' (Norris and Phillips 2003, p. 229). So, we can ask, 'Is this what scientific literacy means?' – the factual question about usage. More important, however, is that we were making a proposal that the science education field ought to include this way of thinking about scientific literacy in setting curricular goals. So we can ask whether this is a sensible, worthwhile, and productive way to think of scientific literacy – the value questions about adoption.

One might wonder whether all concepts are programmatic to some extent. If they are not, what are some concepts that are not programmatic? Consider the chemical concept of an element – that is, a substance consisting of atoms, all of which have the same number of protons. To argue that the concept of element is programmatic requires showing how it expresses value choices that embody programs of action. It might be argued, for example, that the concept arose from the desire for simplicity in theories that explain the natural world. However, unlike the concept of scientific literacy, over which we can exercise almost limitless discretion in adjusting its meaning, the concept of element captures the very real state of affairs that the substance of the world comes in discrete types – such as gold, which has exactly and always 79 protons in its atoms. Consider the concept of π, that is, the ratio of the circumference of circles to their diameters. No doubt, the concept arose from thinking driven by a set of values, including perhaps curiosity. Yet, it is difficult to imagine alternative conceptions to π. Alternatives to programmatic concepts are not only easy to imagine but seem invited by programmatic concepts such as scientific literacy. The concept of π refers to an unalterable fact about a precise geometric shape – its meaning, as the unique ratio of circumference to diameter, is beyond debate (although its exact value is actually beyond knowing). Thus, although most, or perhaps all, of our concepts contain in their history some elements of judgement and choice based upon values, that does not make all of our concepts programmatic. Only those concepts whose value choices embody programs of action about which we can expect significant and indefinitely extended debate fall into the programmatic category.

To summarize: to advance a conception of education, of any sort, is a programmatic task. That is, we promote certain educational ideas for consideration because we assume that certain paths and goals of development and growth are more valuable than others. These assumptions are underpinned by a wide range of premises about what counts as epistemically, morally, or politically valuable. As a result of this reality in educational discourse and thought, responsible practice requires an awareness of, and justification for, these values that underlie our assumptions. Science education is no exception to bearing this burden of responsibility. Discussion of scientific literacy, in particular, would benefit from precisely the sort of analysis we are recommending.

40.2 Programmatic Elements in Conceptions of Scientific Literacy

Using Google Scholar™, we searched for articles published since 2000 using the search phrase ‘scientific literacy’. We identified 74 articles in which we could isolate a definition of scientific literacy. Within these 74 articles, we identified a subset of 62 for which we could classify either the scientific literacy objectives espoused, the justification for espousing those objectives, or both of these. That is, there are two main categories of value discussion at play in contemporary conceptions of scientific literacy. The first regards the value *classification* of the desired outcomes of scientific literacy. The second regards the value *justification* provided (or implied) for such desired outcomes. These two categories, it will be shown, serve to draw attention to the important value analysis required of various conceptions of scientific literacy.

40.2.1 Value Classifications of Desired Outcomes

A focused reading of the 62 sources yielded the observation that many in the field would expect: the outcomes of scientific literacy do not belong uniformly to one value category. Rather, we saw repeated use of a relatively small set of key concepts: knowledge, ability, understanding, independence, participation, appreciation, among several others. One can discern several groupings in this list. Knowledge and understanding are (loosely speaking) epistemological concepts dealing with a mental state someone might possess. One might possess, for example, an understanding of particular scientific propositions or have knowledge of how to calculate the propagation of errors of measurement. Ability likely is interpreted best as a capacity to engage in particular actions. Independence and appreciation, in contrast to the preceding two categories, are states of personal character. We describe persons as more or less independent, and we say that persons are more or less appreciative, with reference to descriptions of whom those persons are and of what they are said to do. One might have knowledge or ability without the concomitant disposition to do anything in particular to use them. Independence and appreciation are, on the other hand, dispositional ways of being (Riveros et al. 2012). It is for this reason that we find it valuable to categorize the proposed outcomes of scientific literacy into three categories of values: values regarding the states of *knowing* one might obtain, values regarding the *capacities* one might refine, and values regarding the personal *traits* one might develop. We call them all values because they refer to ends of science education that are judged desirable.

This schema, or closely related ones, has been identified by others. For example, Laugksch (2000) produced a similar division. After examining the historical development of conceptions of scientific literacy, he concluded that three categories of what it means to be scientifically literate are applicable: being learned, competent, and 'able to function minimally as consumers and citizens' (p. 82). His schema, similar to the one proposed by us above, denotes a move from possessing particular knowledge and understanding, to the possession of certain capacities, to the fulfilling of certain roles. This third category, it should be noted, is not explicitly dispositional (as our third category is). Laugksch maintained ability as the key element of the third category, rather than explicitly separating capacity from disposition to act. Nevertheless, it is difficult to imagine that he desires people who are *able* to function as citizens while being indifferent to whether they do function in that way. Thus, we believe that Laugksch likely had dispositions in mind when formulating his schema, even if he did not explicitly use dispositional language.

The division between knowledge, capacities, and traits of character is pedagogically significant because it draws attention to the unique status of these three forms of valuable outcomes. To say that students should know certain things is clearly pedagogically distinct from saying that they should be able to do certain things. To say that students should embody certain traits, and hence be certain sorts of persons, is strikingly different from both knowledge and capacity.

Table 40.1 indicates which categories of objectives, if any, were evident in each of the sources. We have indicated the presence of objectives with bullets. In those cases marked with a bullet, we are confident there is positive evidence that the referenced objective is included. In those cases without indicator bullets, we did not uncover positive evidence, but another read, or another reader, might find implied evidence present. The knowledge and capacity objectives were widely present, occurring in 59 and 60 of the sources, respectively. The traits objective was also represented well by 38 of the sources.

40.2.1.1 Knowledge

Even though nearly every source said that knowledge is a goal of scientific literacy, it was frequently difficult to find statements of exactly what knowledge was desired. Take, for example, the following statement from Foster and Shiel-Rolle (2011, p. 85): 'At its simplest, the concept of "scientific literacy" refers to the fundamental knowledge that the general public needs to understand about science so that individuals can use that information to make informed decisions regarding personal, civic, and economic matters…'. Such a statement provides a very general idea of the function that the scientific knowledge is intended to serve, but it provides no indication of what that knowledge actually is. Is the knowledge substantive scientific knowledge? Is it, as the words invite one to think, knowledge about science, rather than knowledge of substantive science itself? Later in the same article, however, when describing a summer science camp designed to 'enhance scientific literacy in rural communities' (p. 87), the authors are very specific about the sorts of knowledge required: for example, 'identify the four species of mangroves found within the Bahamas; understand how mangroves serve as nurseries for juvenile fish and stingrays … a basic geological understanding of cave formation in the Bahamas' (p. 90). One might then wonder whether this very specific knowledge is the sort that

Table 40.1 Presence of scientific literacy objectives, political justifications, and moral justifications within cited works

	Objectives			Political justification		Moral justification		
Citations	K	Ca	T	L	Cm	V	P	U
Baker et al. (2009)	●	●			●			
Baram-Tsabari and Yarden (2005)	●	●	●	●				
Bhathal (2011)	●	●	●		●		●	
Bonney et al. (2009)	●	●	●					
Britsch (2009)	●	●						
Brossard and Shanahan (2006)	●	●		●				
Brown et al. (2005)	●	●	●	●	●	●	●	●
Bybee (2008)	●	●	●	●		●	●	●
Bybee (2009)	●	●	●	●			●	●
Bybee and McCrae (2011)	●	●	●	●				
Bybee et al. (2009a)	●	●	●	●				●
Bybee et al. (2009b)	●	●	●	●				●
Cajas (2001)	●	●		●				
Cavagnetto (2010)	●	●		●	●			
Chen et al. (2009)		●		●	●			●
Colucci-Gray et al. (2006)	●	●	●	●	●			●
Cook et al. (2011)	●	●						●
Correia et al. (2010)	●	●	●	●			●	●
DeBoer et al. (2000)	●	●	●	●	●		●	●
Derry and Zalles (2011, April)	●	●		●	●			
Dillon (2009)	●	●	●	●	●	●		●
Dos Santos (2009)	●	●	●	●	●	●	●	●
Eijick and Roth (2007)	●	●	●					
Evans and Rennie (2009)	●	●	●					
Fang (2005)	●	●	●		●			
Feinstein (2011)	●	●		●	●		●	●
Foster and Shiel-Rolle (2011)	●	●	●	●				●
Fuselier and Nelson (2011)	–	–	–	–	–	–	–	–
Gawalt and Adams (2011)	–	–	–	–	–	–	–	–
George and Brenner (2010)	●	●	●	●				●
Greenleaf et al. (2011)	●	●	●			●	●	●
Hobson (2008)	●	●		●				●
Holbrook and Rannikmae (2009)	●	●	●	●		●	●	●
Hondou et al. (2011)	●							
Howes et al. (2009)	–	–	–	–	–	–	–	–
Knain (2006)		●			●			
Krajcik and Sutherland (2010)	●	●		●				●
Lau (2009)	●	●	●	●				●
Laugksch (2000)	●	●	●	●	●	●	●	●
Lee (2004)	–	–	–	–	–	–	–	–
Lee et al. (2005)	–	–	–	–	–	–	–	–
Lee and Roth (2003)	●	●	●	●	●	●	●	

(continued)

Table 40.1 (continued)

	Objectives			Political justification		Moral justification		
Citations	K	Ca	T	L	Cm	V	P	U
Lima et al. (2010)	●	●	●	●	●			●
Marks and Eilks (2009)	–	–	–	–	–	–	–	–
Mbajiorgu and Ali (2003)		●		●				●
McConney et al. (2011)	●	●	●	●	●		●	●
Millar (2006)	●	●	●	●	●			
Millar (2011)	–	–	–	–	–	–	–	–
Murcia (2009)	●	●	●	●	●	●		●
O'Neill and Polman (2004)	●	●	●	●			●	
Patrick et al. (2009)	–	–	–	–	–	–	–	–
Pearson et al. (2010)	●	●						●
Porter et al. (2010)	●	●						
Rannikmae et al. (2010)	●							
Rennie and Williams (2002)	●	●		●				
Reveles and Brown (2008)	●	●			●			
Reveles et al. (2004)	●	●	●		●			
Rheinlander and Wallace (2011)	–	–	–	–	–	–	–	–
Ritchie et al. (2011)	●	●	●	●				●
Roth and Lee (2002)	●	●			●			
Rughinis (2011)	●	●	●	●				
Sadler (2011)	–	–	–	–	–	–	–	–
Sadler and Zeidler (2009)	●	●	●	●	●			
Schroeder et al. (2009)	●	●	●	●	●			
Shwartz et al. (2006)	●	●	●	●	●			
Soobard and Rannikmäe (2011)	●	●	●	●				
Sullivan (2008)	●	●						
Thomson and De Bortoli (2008)	–	–	–	–	–	–	–	–
Turner (2008)	●	●	●	●	●		●	●
Wallace (2004)	●	●			●			
Wang et al. (2011)	●	●						
Webb (2010)	●	●						
Yarden (2009)	–	–	–	–	–	–	–	–
Yore et al. (2007)	●	●	●	●	●			●
Totals	59	60	38	41	28	9	15	29

Objectives- *K* knowledge, *Ca* capacities, *T* traits
Justifications- *L* liberal, *Cm* communitarian, *V* virtue, *P* principled, *U* utilitarian

is needed 'to make informed decisions regarding personal, civic, and economic matters' as the authors want scientific literacy to provide.

Lau (2009) recognizes that the expression 'scientific knowledge' can be used pejoratively, perhaps to mean content learned by rote: 'Local science educators found that the junior secondary science curriculum was dominated by scientific knowledge, leaving many important scientific processes and understanding of the nature of science untouched' (p. 1062). At times, Lau appears to prefer the term 'understanding' to pick out what is valuable for scientific literacy, but he especially presses the distinction between knowledge of science and knowledge about science. The former he sees as referring to the substantive content of science; the latter as referring to meta-scientific knowledge, that is, to knowledge about scientific knowledge.

40.2.1.2 Capacities

Gräber et al. (2001) suggest 'a competency based model of scientific literacy' (p. 209). Including neither knowledge nor traits on the face of it, but instead focusing on capacities, this could be one of the most radical positions in the field. When examined more closely, however, a three-way distinction similar to our own underlies their model. They suggest that scientific literacy is needed 'for the individual to cope with our complex world' (p. 209), and to shape the sort of scientific literacy needed for this task, three questions must be answered: What do people know? What can people do? What do people value? They answer each question with sets of competencies, even the question about knowledge, for which they cite the need for subject competence and epistemological competence. The subject and epistemological competence fit under knowledge as we define it. The competencies they include under their second question are what we mean by capacities: social competence, procedural competence, and communicative competence.

Capacities often shade into knowledge, depending upon how the nature of the capacity is formulated. For example, Bybee (2009) says the following: 'the student with less developed scientific literacy might be able to recall simple scientific factual knowledge about a physical system and to use common science terms in stating a conclusion' (p. 2). On the one hand, Bybee is speaking of capacities (being able to recall something, and using something); on the other hand, he is thinking about the factual and terminological knowledge a student has. We see no deep theoretical point in this discrepancy that arises from vagaries of English usage nor any important issue that hangs on settling it.

40.2.1.3 Traits

The traits we identified fell into two major groups: intellectual and moral traits, the second of which are often termed 'moral virtues'. Intellectual traits are characteristics of people that promote intellectual flourishing. These traits might include inquisitiveness, open-mindedness, and carefulness. Virtues are characteristics that promote moral flourishing. These virtues might include honesty, generosity, and courage. Clearly, there are connections between the categories because a virtue such as honesty is central to intellectual flourishing, and a trait such as open-mindedness can be seen as morally superior to its opposite. Evans and Rennie (2009) associate scientific literacy with traits when they say that it is the capacity 'to be interested in, and understand, the world around them … to be sceptical and questioning of claims made by others about scientific matters …' (pp. 25–26).

40.2.2 Value Justifications for Desired Outcomes

This is the point at which our second categorization becomes relevant. If it is the case that there are three broad sorts of valued outcomes being considered in discussions about scientific literacy, then these differing values might very well demand and attract differing forms of justification. Table 40.1 indicates that we identified two broad categories of justification for scientific literacy objectives: moral and political. 'Morality' can be used in a descriptive or normative sense. In the descriptive sense, 'morality' refers to a code of conduct put forward by or followed by a society. You might imagine an anthropologist observing and interacting with a society and from the data collected inferring the code of conduct adopted in that society. If the descriptive sense is taken to exhaust the meaning of what is moral, then what is moral simply refers to the code of conduct that any group or person adopts. If the descriptive sense is taken in this way, then it conflicts with the normative sense of 'morality'. In the normative sense, what is moral is taken to apply universally, that is, to all those 'who can understand it and govern their behavior by it' (Gert 2011, p. 1). In the normative sense, it is assumed that actual codes of behaviour do not necessarily capture what it means to be moral. Actual codes of behaviour can be analysed and critiqued for falling short on morality, where morality here is thought of as an ideal that exists outside human practices and to which those practices can be held accountable. In the normative sense, moral justifications can never be overridden by other non-moral considerations.

Moral justifications of the objectives of scientific literacy can thus refer either to codes of conduct that are actually adopted or to codes of conduct that are not adopted but which, upon reflection, ought to be adopted. In the first type of case, the moral justification would be cast in terms of whether the objective led to behaviour that was in accord with an accepted code. In the latter type of case, the justification would be cast in terms of whether the objective led to behaviour that was considered moral, regardless of its conformity to an accepted code. If the behaviour was in conflict with an accepted code, the justification would in effect be saying that the code was morally deficient.

On one account, political justifications reduce to moral ones. That is, a behaviour is politically justified if, and only if, it is morally justified. On another account, moral justification is a necessary but insufficient condition for political justification: a behaviour is justified politically, only if it is morally justified. Consider an example outside of science education. If it is accepted that it is morally wrong to kill other human beings outside of situations of immediate threat to one's own life, then no reference to possible beneficial consequences can ever provide a political justification sufficient to override the moral condemnation of the act.

Politics can be defined roughly as the method by which groups of people make collective decisions. In advanced societies, politics is largely about how governments function, the business of collective decision making having been assigned to governments for many of the societies' resources. In this light, a political justification can be seen as one that defends a particular distribution of resources or the means of that distribution. So conceived, political justification requires more than mere consent from those affected by the decisions taken. The justification requires the offering of publicly accessible reasons that can be understood and challenged. It is through the public display and vetting of reasons that the political decisions acquire legitimacy; legitimacy cannot be bestowed by acquiescence.

A tight connection between political and moral justification is difficult to avoid, because the distribution of limited resources needs to conform to a sense of justice. So, although the distribution of resources is a practical matter and the form that distribution takes can be defended in part on practical grounds, it is impossible to avoid questions of fairness in the distribution. Education is one of the limited resources that our society has available for distribution. Therefore, political justifications of decisions of how to distribute that resource must ultimately conform to the demands of justice and be seen as legitimate on the basis of the reasons used to defend them.

40.2.2.1 Types of Moral Justification

The most prominent form of moral justification we uncovered in this analysis was *utilitarian*, found in roughly one-half the cases. Classical utilitarianism holds that actions are good insofar as they produce the most overall happiness (McLachlan 2010) or the greatest good for the greatest number. Debates rage over what constitutes happiness and over whether happiness is the greatest good that is to be sought. Whatever the particulars, utilitarianism is a form of consequentialism, which is a family of views that holds that the goodness or morality of an action is to be judged by its effects. In the case of justifying the objectives of scientific literacy, utilitarianism is manifested primarily on economic grounds, via an analysis of the sort of literacy that contributes to a healthy economy and personal competitiveness in the job market. Laugksch (2000) notes, for example, that advanced economies require technologically skilled professionals and only a scientifically literate populace can produce such professionals. Scientific literacy, on this understanding, is good because it strengthens economies and personal economic competitiveness. These consequences are, presumably, thought to be conducive to overall good or to human happiness, bringing us back to the touchstone of utilitarianism. Thus, the moral justification for scientific literacy might be outlined as follows: a society is economically stronger in the long term when its citizens are educated to a certain level of scientific literacy. An economically strong society is better for the persons encompassed by it. Therefore, it is justified to pursue scientific literacy for citizens.

Foster and Shiel-Rolle (2011) provide a utilitarian argument for scientific literacy that is almost textbook in its adoption of the utilitarian view described above:

> The importance of developing a scientific literate society is multifaceted. First, increasing scientific literacy has been considered to be a critical strategy for maintaining a country's technological and economic standing … Second, [i]t is increasingly important to have a scientifically literate society to make informed decisions regarding policy development and

> its implementation. Lastly, … [s]cientifically literate international communities can … potentially use the scientific insight to improve their local agricultural and marine practices, economies and educational systems. (p. 86)

So, although they see the reasons for promoting scientific literacy as multifaceted, all of their reasons fall into the same category: utilitarianism.

Bybee (2008) provides the following utilitarian moral justification for scientific literacy in the context of environmental issues and PISA 2006:

> Scientific literacy is essential to an individual's full participation in society. The understandings and abilities associated with scientific literacy empower citizens to make personal decisions and appropriately participate in the formulation of public policies that impact their lives. Assertions such as these provide a rationale of scientific literacy as the central purpose of science education. Too often, however, the rationale lacks connections that answer questions such as "personal decisions—" *concerning what*?" "fully participate—*in what*?" or "formulate policies—*relative to what*?" One could answer these questions using contexts that citizens daily confront; for example, personal health, natural hazards, and information at the frontiers of science and technology. Two other domains stand out—national resources and environmental quality. (pp. 567–568)

Readers would be correct to object that this evidence is insufficient to establish that Bybee relies upon a utilitarian justification for scientific literacy. Thus, it is necessary to examine his text in greater detail. Further examination of his document leaves little doubt about the nature of his justification. For example, he frames four policies that are supported by fostering scientific literacy as he conceives of it. The first policy is the fulfilment of basic human 'physiological needs such as clean air and water and sufficient food' (p. 578). The second and third policies come down to the same justification. The second policy deals with 'maintaining and improving the physical environment' (p. 578), which is 'the common heritage of humankind, and they are essential to fulfilling basic needs' (p. 579). The third policy focuses on the wise use of natural resources, which 'is closely related to … fulfillment of both the physical environment and to fulfillment of basic needs' (p. 579). Finally, the fourth policy aims 'toward establishing a greater sense of community' (p. 579). As such, the fourth policy might appear to find its grounding in communitarianism. In addition, the policy refers to the reduction of 'prejudice, such as racism, sexism, ethnocentricism and nationalism' (p. 579). This aim leans toward some sort of principled justification of avoiding forbidden behaviour. However, it is clear that both the push for community and the reliance on principles are themselves grounded on the same urge to fulfil basic human needs: 'If fulfillment of human needs and improvement of the environment … are to become realities, we must increase community involvement… one of the first steps … is the elimination of prejudicial barriers to community' (p. 579). Thus, the second to fourth policies reduce to the first, which clearly is motivated on utilitarian grounds. Feinstein (2011) makes a very deliberate effort to argue that the utilitarian justification for scientific literacy is the most robust:

> This essay examines the idea that science education is useful in daily life . . . I focus on usefulness for two reasons. First, claims about the usefulness of science education are more testable than claims about its cultural, aesthetic, or moral value. In other words, when someone says science education is useful in a particular way, we should be able to find evidence for or against that claim, at least in theory. Second, the idea that science education is useful

> exerts a powerful political influence: People, particularly people with money and resources, seem to believe in it . . . It is important to specify what I mean by "useful in daily life," because that phrase has several possible interpretations. I am referring to the very specific notion that science education can help people solve personally meaningful problems in their lives, directly affect their material and social circumstances, shape their behavior, and inform their most significant practical and political decisions. (p. 169)

Feinstein's argument is very interesting. He claims to prefer utilitarian justifications because they are more testable than moral justifications. However, as we have shown, utilitarianism is one form of morality, namely, the form that focuses on the consequences of actions to decide on their morality, so Feinstein's attempt to separate the good from the useful fails to recognize that usefulness is just one way to interpret goodness. As Feinstein claims, consequences might also prove testable, supposedly making the judgement that science education is useful more clear-cut. Yet, the calculation is not so easy as Feinstein envisages. He sees usefulness as measured by helping people solve personally meaningful problems and by informing their most significant decisions. Deciding whether a problem is personally meaningful or a decision is of greatest significance also involves moral judgement that cannot be reduced to utility calculation.

The next most frequently found type of moral justification was based upon *principles*. Principled justification (deontology, in technical terms) concerns itself with what is morally forbidden, required, and permitted. It stands in contrast to varieties of consequentialism in that it holds that conformity to moral norms, such as particular duties or principles, makes actions morally praiseworthy (Alexander and Moore 2008). In its Kantian form, for instance, one seeks to ascertain the principle (or *maxim*) underlying a particular proposed action. This principle is then tested by asking if it could be applied universally, including to oneself. Praiseworthy actions, in Kantianism's simplified form, are those that satisfy these two tests. It is because of these reasons that deontologists hold that actions cannot be judged by their effects alone: according to this view, some actions are forbidden no matter how good their consequences might turn out.

Laugksch (2000) notes, for example, that it is often argued that citizens ought to be scientifically literate because they are affected by science, because they help to fund scientific research through tax dollars, and because they can participate in public deliberation when they are informed about scientific issues. In each of these cases, the fundamental justification is not that greater good is produced through scientific literacy (as in utilitarian justifications), but rather that certain principles are best satisfied when citizens are helped to become scientifically literate: such as, we should be informed about those matters that affect our lives, we should understand what we help to support through tax dollars, or that all citizens ought to participate in public decision making. These principles generally refer to conceptions of ethical governance. Since the criteria in this reasoning are most related to the satisfaction of certain ethical principles (such as democratic sovereignty), this sort of reasoning is best categorized as principled or deontological. Thus, a person holding that participation in public deliberation is a right might not be deterred in holding this view just because some people are not scientifically literate, are unable to participate in deliberations about scientific issues, but nonetheless show no ill effects from their lack of participation. Nor need the person be deterred by public deliberation that reached poorer choices than might be reached by a much narrower blue-ribbon panel. Once more, abiding by the principle is much more important than the consequences.

Bhathal (2011) makes the argument that Indigenous persons are underrepresented in science classes and in scientific careers, the implication being that this situation in principle is wrong. Although not explicitly argued by Bhathal, the underrepresentation seems to be thought of as a violation of the moral right to non-discrimination and equality. Bhathal describes a study in which 15 secondary school Aboriginal students were brought to a university six times during a semester to conduct projects in astronomy. The projects drew upon both Aboriginal astronomy and modern scientific astronomy and aimed to improve the students' scientific literacy. It is mildly curious to us that in the outcomes section at the end of the article, several utilitarian ends were cited in an apparent justification of the intervention that had taken place: students developed more positive attitudes toward science, gained knowledge of Aboriginal astronomy, were interested in the projects, and more were disposed at the end of the projects than at the beginning of them to continue with their high school education. Of course, all of these outcomes are positive and important. Our mild curiosity stems from the fact that none of these findings refers to the original justification for undertaking the projects, which was principle-based rather than based on utilitarian outcomes. Presumably, the justification runs as follows: the utilitarian ends achieved are indicators that teaching scientific literacy through astronomy addresses the underrepresentation of Aboriginal students in science, which is deplorable on principle. However, none of this argumentation is made explicit, so it is possible that we are putting words into the authors' mouths that they would not accept.

The same sort of principle-based justification is also present with respect to gender representation in George and Brenner (2010). As stated by the authors, 'The goal of the project was to create opportunities in college curricula that urge women to take science seriously whether or not they are science majors, to learn how science orders and explores the world, and to question it along the way' (p. 28). Although it is never put so explicitly, it seems the principle justifying this goal is that there ought not be a major difference in the representation of males and females in science. At the end of their report, the authors say: '… we cannot conclude that introducing feminist science studies improved the students' learning compared with a more traditional science course. Still, by introducing this course into the women's studies and science for the liberal arts curricula, we have built at least one two-way street across what has been an intimidating intellectual divide' (p. 34). Improving learning was a utilitarian goal of this project, but it was secondary by the authors' own admission. The primary goal was the increased representation of women in science. Thus, the authors seem to hold fast to their original principled stance in the previously quoted extract. Although the authors do not explicitly say, 'Even though we cannot show improved learning …', it appears that this is what they have in mind. That is, they can nevertheless claim success despite no evidence of improved learning because they have found evidence that their approach can successfully address lower female participation rates in science, their principled objection to which is their primary justification.

In addition to utilitarian and principled justifications, one also finds conceptions of scientific literacy supported by *virtue theoretical* arguments, though these are the least frequently appearing type of justification. Virtue theoretical arguments are about human character and excellence (Hursthouse 2010). As such, they stand in contrast to arguments about doing what one is obliged to do or acting so as to produce desirable consequences. Also as such, the virtuous person is not simply one who practises virtuous acts, such as truth telling. Rather, truth telling is practised because it is valued for its own sake. We also need to distinguish two broad categories of virtue: namely, moral virtue and intellectual virtue. Among the first category we might find benevolence, compassion, empathy, gentleness, and selflessness. Among the second category we might find detachment, determination, flexibility, open-mindedness, perseverance, and reliability. We do not mean these lists to be comprehensive or mutually exclusive. For example, open-mindedness is intellectually virtuous in the conduct of science because it can prompt the consideration of alternative explanations that might be more powerful than the one under consideration. Likewise, open-mindedness is morally virtuous in everyday dealings with others because it can lead to the respect of moral agents who nevertheless hold different views and practise different customs than oneself.

Laugksch (2000), for example, discusses 'the intellectual, aesthetic, and moral benefits of scientific literacy to individuals' (p. 86). He describes these mostly in terms of intellectual virtues such as 'cultivated mind' and 'educated person', and perhaps a moral virtue, 'not merely wiser but better' (p. 86). Notions of cultivation and betterment are, at their root, notions of human excellence. Scientific literacy, in this case, is valuable insofar as it contributes to making students better persons. This emphasis places his reasoning within the category of virtue theory and places the focus on individuals' characters as opposed to, say, their knowledge and capacities.

It is striking that Dillon (2009) noted the concern of members of the 2007 Linné Scientific Literacy Symposium to the effect that there was a lack of emphasis on virtue in school science: 'There is little flavour in school science of the importance that creativity, ingenuity, intuition or persistence have played in the scientific enterprise' (Members of the Linné Scientific Literacy Symposium 2007, p. 7). In the same discussion, Dillon notes a particular emphasis on virtue in the reformed science education curriculum of Turkey and remarks that this emphasis would be 'unusual to a Western European eye' (2009, p. 208). He exemplifies the unusual emphasis with the following desired outcomes among others: 'Self-disciplined (Self-controlled, prompt, self-evaluating, sincere, consistent)' (Taşar and Atasoy 2006, p. 9). All of these outcomes belong among those on lists of intellectual and moral virtues.

Murcia (2009) says that scientific literacy is 'about a way of thinking and acting' (p. 219). This statement suggests she might be providing a virtue justification for scientific literacy. Although in Table 40.1 we have marked this work as providing virtue justification for scientific literacy objectives, we are not completely confident that it does. Murcia develops a framework of scientific literacy and says: ‘The aim of this framework was to clarify the type of knowledge, roles and abilities required to act scientifically in a contemporary context’ (p. 218). Among her categories, one of the ‘roles’ is the one most closely related to the nature of character. She refers to the work of Ford and Forman (2006), who have named the roles of Constructor and Critiquer for scientifically literate people. The latter of these, in particular, is easily interpreted in terms of the intellectual virtue of criticalness, the former can perhaps be interpreted in terms of creativeness. We are tentative in these recommended interpretations of Murcia’s work because we are not sure that is what she meant. Nevertheless, interpretation in terms of intellectual virtue does make sense of this aspect of her work.

Although Holbrook and Rannikmäe (2009) call them ‘skills’, we take their ‘personal skills related to creativity, initiative, safe working’ (p. 283) to be personal qualities much the same as virtues. Similarly, although Dos Santos (2009) never uses the word ‘virtue’, his entire article is about a particular sort of virtue, namely, commitment: ‘The conclusions of those works [Freire’s] reveal a political commitment to struggle for liberation’ (p. 369); ‘students need to take part directly in SSI discussions, so they can interact with the world, discuss their living conditions, and become committed to social change’ (p. 374). The clear implication of these lines is to point to the desirability of a particular sort of character trait, that is, one of commitment to social change.

One article (Greenleaf et al. 2011) presented all three types of moral justification.

Regarding principled moral justification, there is a repeated emphasis on inequity and underrepresentation as a motivating force. Specifically, they note underrepresentation of certain cultural groups in science and inequity of resources and training for teachers. The core argument is that illiteracy and lack of scientific literacy are objectionable on the grounds that they foster inequity (a deontological concern when framed in this way). Here is an example excerpt:

> Withdrawing adolescents from instruction in science to remediate reading difficulties threatens to exacerbate historic inequities in achievement for populations of students traditionally underrepresented in the sciences … There is therefore increasing urgency to investigate how the integration of reading instruction into science learning at the high school level might advance the reading and science achievement of underachieving youth. (p. 649)

Utilitarian justifications are found straightforwardly. The article opens with the standard argument about how the health of the nation (the United States in this case) requires this sort of education for scientific literacy on grounds of both economic and democratic utility: ‘Our democracy and future economic well-being depend on a literate populace, capable of fully participating in the demands of the twenty-first century … Yet National Assessment of Educational Progress (NAEP) results indicate that most American youth lack the skills to successfully engage in the higher-level literacy, reasoning, and inquiry needed for an information-generating and information-transforming economy’ (p. 648).

Although they are the most ambiguous of the three sorts of justification found in this article, we believe a case can be made that Greenleaf et al. offer virtue justifications for scientific literacy. They refer on several occasions to dispositional outcomes, suggesting that they are concerned with individuals' characters, but they seem to go further and to frame some dispositions in virtue terms. For example, they explicitly say that they want 'resilient' learners and students with 'stamina' (pp. 657–658) and construct the issue as one of personal identity construction. When we use terms of personal excellence, and we note that we seek to have people develop into certain sorts of people, we have moved from discussion of ordinary cognitive and attitudinal traits to discussion of virtues, either prudential or moral.

40.2.2.2 Types of Political Justification

Approximately two-thirds of the articles appeal to political liberalism to justify their scientific literacy objectives. Liberal theory places a fundamental emphasis on the exercise of personal freedom. One ought to be free to determine for oneself important elements of personal belief and lifestyle (such as religious belief). Rawls (1993), for example, famously argued that a political community ought to be arranged so that free persons could participate in rational public debate and dialogue in spite of their diverse beliefs. The educational corollary to this position is that persons must be nurtured into the knowledge, capacities, and traits required to participate in such critical deliberation. When public questions regard scientific practice or regulation or depend on scientific knowledge and method, it follows that scientific literacy specifically is required. One might argue, therefore, that the requirement to support public democratic deliberation is not just a principled moral imperative (as we argued prior to this section) but is also a liberal political imperative.

Correia et al. (2010) provide a textbook case of a liberal justification for scientific literacy:

> Scientific literacy (SL) is necessary in post-industrial society to nurture an autonomous citizenry . . . We are negotiating a new contract between society and science, and all citizens must have the right and the ability to make their own judgments about the ethical aspects of scientific and technological issues. (p. 680)
>
> Scientific literacy is a novel requirement for producing informed and autonomous citizens in post-industrial societies. Moreover, it is necessary that a student achieve scientific literacy during his or her career in higher education to be able to achieve the education for sustainability. Universities striving to teach sustainability must graft a holistic perspective onto the traditional specialized undergraduate curriculum. This new integrative, inter/trans-disciplinary epistemological approach is necessary to allow autonomous citizenship, that is, the possibility that each citizen understand and participate in discussions about the complex issues posed by our contemporary post-industrial society. (p. 685)

Bybee (2009) expresses a clear emphasis on the capacity of individuals to take a position on personal and political decisions and to formulate arguments in support of it:

> . . . as people are presented with more, and sometimes conflicting, information about phenomena, such as climate change, they need to be able to access collective scientific knowledge and understand, for example, the scientific basis for evaluations . . . versus the

> basis for perspectives by individuals representing oil, gas, or coal companies. Finally, citizens should be able to use the results of scientific reports and recommendations about issues such as health, prescription drugs, and safety to formulate arguments supporting their decisions about scientific issues of personal, social, and global consequence. (pp. 3–4)

These examples from Correia et al. and Bybee are clear instances of liberal political justification because they explicitly emphasize individual decision-making capacity, not collective meaning or collective agency. It is worth noting that, even though most of the articles contained in our review have a liberal justification at play for the objectives of scientific literacy, these justifications were nearly always vague references to individual decision-making capacity rather than explicit invocations of liberal theory. We think it is fair to say that the scientific literacy literature assumes liberal politics in most cases, in contrast to defending liberalism.

Also, there is not always a clear divide between liberal justifications and moral ones. There seems to be a moral implication in O'Neill and Polman (2004) when they discuss why people need scientific literacy to understand their personal choices:

> We suggest that on a societal scale, schools would function more effectively if they covered less content, in ways that would allow students to build a deeper understanding of how scientific knowledge claims and theories are constructed. This would be of use to all students in their decision making outside of school, and beneficial to those pursuing postsecondary studies in science as well. (p. 237)

The primary justification here for teaching about the nature of science seems to be the assistance this knowledge would bring to decision making outside of school. This justification is phrased in fairly standard liberal civic terms, meaning something like 'all agents should be able to access and understand information relevant to their personal choices'. Such a justification can be interpreted as well in Kantian moral terms, which is not surprising given that liberal political theory has a strong deontological heritage. This often displayed union of political liberalism and Kantian ethics in education points to a linkage between the discussion in this section on types of political justification with the foregoing section on types of moral justification.

The most explicit uses of political theory in these articles were instances in which communitarians wanted to distance themselves from the assumption of liberal politics. About one-half of the articles appealed to communitarian justifications for scientific literacy. Liberalism in educational theory often is contrasted with communitarianism (e.g., Strike 2000). Liberalism holds primary the fair distribution of liberties and resources to enable the individual selection of forms of life to lead. Fairness according to communitarianism must be judged within traditions and thus can vary from society to society and from time to time. In communitarian political thought, the emphasis is placed primarily on the collective determination of the community, not on the autonomous choice of the individual. Sectarian schools are, for example, a prominent manifestation of communitarian religious thought. Rather than emphasizing individual choice and deliberation across communities, communitarian politics seeks to nurture a single community. Of course, given the presumption of communitarianism that standards of value are community-specific, communitarians in plural states must be prepared to accept many communities. Such political reasoning can be applied also to scientific literacy. When science educators speak of fostering scientific values, for instance, they are at least partially speaking about creating and nurturing a particular kind of shared community – in this instance, one based upon science. At its root, this is a communitarian stance.

There are two broad kinds of communitarianism reflected among the articles. The first is represented in articles like Dos Santos (2009). This article uses a Freirean approach to emphasize community meaning and knowledge. The point of the article is to advance the ways in which a particular community constructs its problems and knowledge. Dos Santos draws attention to the existence of landfills in many Brazilian cities to illustrate how Freirean pedagogy could turn this situation into an important science lesson. 'Teachers could take their students to visit landfills, to interview people that work there, and later discuss in the classroom how that community could change the situation' (p. 373). The assumption of the collective determination of the community in setting its future is quite explicit in this quotation. Consider another situation mentioned by Dos Santos in which a school is situated in a location without a sewer system. 'The search for solutions for this problem will inevitably point out the need of mobilizing the school, and local community for political actions aimed at providing that community with sewage' (p. 374). Again, we see the emphasis on community decision making and action as opposed, let us say, to individual decision making and action, such as individual home owners installing septic systems or composting toilets. Note also that the political theory at play in the Dos Santos' document is much more explicit than in nearly all of the examples that drew upon liberal theory.

The second kind of communitarianism found in the articles places an emphasis on drawing students into scientific culture. In articles such as these, scientific literacy is justified on the grounds that it draws people into science as a cultural act. Such a justification seems centrally communitarian and quite distinct from saying that scientific literacy is important because it fosters individual decision making. Cavagnetto (2010), for example, argues that skills in scientific argumentation and understanding scientific processes and principles are insufficient bases in scientific literacy. Such skill and knowledge do not initiate one into the culture of science, which can only be entered by engaging in scientific practices. So, the justification for teaching argumentation is not that it teaches argumentative skill, but that it introduces students into a fundamental practice of science: 'Therefore, the goal of argument instruction in the context of scientific literacy is not the transfer of argument skills but rather the transfer of an understanding of scientific practice' (p. 352).

40.3 Choosing Among Conceptions of Scientific Literacy

We have shown thus far that the programmatic elements of various conceptions of science literacy contain at least three categories of valued objectives: knowledge, capacities, and traits. These three categories of objectives are justified either

Table 40.2 Frequencies of political and moral justifications offered for each scientific literacy objective

	Political justifications		Moral justifications		
Objectives	L	Cm	V	P	U
Knowledge	40	26	9	15	27
Capacities	41	28	9	15	29
Traits	31	19	9	14	22

Key. L liberal, *Cm* communitarian, *V* virtue, *P* principled, *U* utilitarian

morally or politically. On the moral side, we documented utilitarian, principled, and virtue theoretical justifications. On the political side, we documented liberal and communitarian justifications. There is no necessary link between any particular category of valued objective and any particular form of justification, and we found no strong correlation in the data, as can be seen by checking the frequencies of types of justifications for each objective in Table 40.2. Nor is it the case that these justifications contradict one another, although they might in certain renditions. Thus, it is possible at least sometimes to use without contradiction more than one type of justification to support the same objective. One could support the development of valuable traits of personality not only on the grounds that they contribute to personal excellence (a virtue theoretical justification) but also because they enable persons to contribute to the overall social good (a utilitarian justification) or also because persons have a moral right to be so supported (a principled justification). Yet, we note that among moral justifications, fewer utilitarian justifications were provided for the trait objective than for other objectives, which makes sense if you consider moral traits to be favoured more for their desirability than their usefulness. These traits might enhance personal participation in democratic deliberation (a liberal justification), or they might allow one to appreciate scientific culture (a communitarian justification). However, we note that between the political justifications, there were fewer communitarian justifications for trait objectives than for other objectives, which makes sense if traits are viewed as individual accomplishments.

Our schema is not totally exhaustive of all the objectives and justifications that do or could exist, so it is possible to propose analytic divisions beyond what we have offered. Returning to the opening of the chapter, the point is that scientific literacy is highly programmatic. This programmatic character is manifested in different kinds of valued objectives and justifications for them. To understand what is at stake in debates about scientific literacy and to decide one's own position, one needs to identify the valued objectives and the justifications for them, to understand how each type of justification functions, and to critique each. The canvass we have done of several examples should provide some useful starting points for such identification, understanding, and critique.

Understanding how the goals of scientific literacy and their justifications are linked allows us better to understand scientific literacy itself, and it allows scholars of science education to ask more fruitful and illuminating questions about this educational ideal. As we have demonstrated, each form of justification focuses on certain aspects of value and not others. The choice of whether to accept a particular justification is educationally significant. The choice is not always easy, and the alternatives among various justifications are not always clearly distinguishable in terms of quality, although we hope that we have provided guidance for making such distinctions.

So how might choices be made among alternative versions of scientific literacy objectives and their possible justifications? Among all the possibilities of contrasting positions defined by crossing the three types of scientific literacy objectives with the five types of justifications, we will consider three contrasts for illustration. The first contrast is between political and moral justifications, the second within political justifications between liberal and communitarian justifications, and the third within moral justifications between virtue, principled, and utilitarian justifications. The entire domain is essentially contested, so that there are not always clearly right or even better positions, but, rather, a panoply of good positions with some clearly poor or not so good ones. This is the nature of the scientific literacy domain; there is no way to make the ambiguity and uncertainty disappear. The point is to identify which definition of scientific literacy comparatively speaking is most educationally significant.

40.3.1 Contrast Between Political and Moral Justifications

At a very general level of consideration, ignoring any specifics for the moment and assuming all other things are equal, moral justifications in the normative sense that we prefer, based as they are upon what is right, should trump political justifications, based as they are upon what is possible. Thus, a moral justification for a science curriculum directed toward a universal scientific literacy that respected gender and racial equality might be seen, all other things being equal, as stronger than a political justification for a curriculum that promoted scientific literacy for social activism. Similarly, aiming to foster individual intellectual and moral virtues such as curiosity, open-mindedness, and valuing fair tests might be seen, *ceteris paribus*, as a more important reason to foster scientific literacy than the creation of critical and informed citizens for the promotion of the democratic state. The *ceteris paribus* clause covers a host of nuance and qualifications. For moral justifications to trump political ones, they have to be sound moral justifications. Thus, for example, if the justification offered is based on providing a gender and racially equal scientific literacy, then the curriculum that is envisaged to do this must be able to result in that desired outcome, or the justification for using that curriculum to reach the desired objectives breaks down. Also, it is one matter to respect gender and racial equality in providing opportunity for scientific literacy development and quite a different matter to demand equal outcomes. Perhaps equal scientific literacy outcomes across gender and race is not the most morally desirable outcome. An argument is needed to make the case one way or the other and that argument needs to be assessed.

Perhaps the best position for science educators is to consider moral justifications offered for scientific literacy objectives before considering the political ones.

There is no calculus, unfortunately – a theme we will repeat – for choosing between strong moral and strong political justifications if they result in the recommendation of different objectives and curricula for obtaining them. The situation is even more complicated, as shown in the following section.

40.3.2 Contrast Within Political Justifications

The distinctions between moral and political justifications are not always so easy to make. The political justifications based on liberalism and communitarianism themselves draw upon moral theory. Liberalism celebrates justice for all in the service of individual autonomy. Communitarianism sees collective decision making as a higher good than individual choice. Theoretical arguments do not exist that can help us choose definitively between these positions. Making the situation more complicated is that proponents on either side often acknowledge the values advocated by the other.

A central feature of liberalism is its neutrality concerning conceptions of what is good. Individuals should be free to follow their own preferences so long as they do not impede others' freedom to follow their preferences, but liberalism makes no judgement on the quality of those preferences. On this conception, scientific literacy has to be seen as a tool to help individuals to choose and pursue their preferred life courses. Communitarians believe that goods must be rank ordered and that there are goods in common. On this view, scientific literacy is seen as one of the common goods that helps build a society.

Does liberal justice trump communitarian benevolence? Does scientific literacy for individual self-determination trump scientific literacy for social cohesion and progress? It is difficult for educators to choose between these positions, because we are used to understanding education itself as good for both individuals and for society. The situation is such that many educators have comfortably chosen both justifications as being sound. We know of no strict contradiction between the positions. Furthermore, we find it difficult ourselves as educators to conceive of a justification for scientific literacy objectives that did not take into account the benefits for both the individual and for the society. This position is not one that we can defend here, but one we are confident would serve well science education. Our comfort rests on several considerations. First, there is no scholarly consensus on which version of political and moral life among those we have discussed is the preferable. Second, although we believe that education cannot be neutral, we also believe that it is not the role of education to select only one version of political and moral life to espouse, if there is more than one viable alternative, which there is. Third, we do believe it is the role of education to introduce students to the various forms of political and moral life that find widespread justification within our society. After all, it is the generation that is now in school that will be the one that has to grapple with these difficult and age-old issues, and for this reason is the one in need of broad exposure to more than one formulation of democratic politics and ethical living.

40.3.3 Contrast Within Moral Justifications

Under certain moral justifications scientific literacy might be argued to be *intrinsically* good, while under others it might not be an ultimate good itself but be an *instrument* for the good. If scientific literacy is part of a flourishing human life (a virtue theoretical argument), then one might conceive of such literacy as a good thing on its own (intrinsically good). If scientific literacy is valuable only insofar as it helps the economy, then it is only an instrument to the good (in this case, wealth or employment and the happiness that flows from those benefits). Such a utilitarian justification leads to an entirely different vision of science education than the preceding virtue theoretical justification. Why, for instance, should we help students to become broadly informed about science when specialization is often more highly rewarded in the job market? The answer to this question, and many like it, requires one to make the kind of distinctions we have begun to introduce here.

This contrast is very similar to the one described in the previous section. Some moral theorists argue that happiness is the greatest good and that the best society is the one in which the total utility is maximized and that utility is spread as evenly as possible across all people. Other theorists argue that individual excellence, in the form of virtues, is the greatest good, and the best society is the one in which people are the most virtuous. We argue for reasons similar to those in the previous section that education cannot choose between virtue and utility. Education can choose moral over immoral or amoral behaviour, but it is not its role to favour one version of morality over another, if all those versions find strong justification within the scholarly community. Therefore, a version of scientific literacy that sought only utilitarian goals could be critiqued on the grounds that it ignored individual excellence; a version focussed entirely on fostering virtue could be faulted for ignoring other important goals, such as the contribution to social utility resulting from making an effort to become scientifically literate.

40.4 Conclusion

We find ourselves in a position of not being able to make, all things being equal, definitive choices among justifications for the objectives of scientific literacy. Education in a way is like liberalism – it cannot (or, perhaps better, should not) choose between comprehensive conceptions of the good. MacLeod (1997) provides an excellent account of the meaning of comprehensive conceptions of the good:

> Conceptions of the good are views about the nature and constitutive elements of a valuable life. Conceptions of the good may be comprehensive or partial. A comprehensive conception of the good attempts to delineate a complete account of the sources and nature of a good life. A partial conception of the good merely identifies particular activities or projects that contribute to the realization of human excellence. Commitment to a religion can constitute a comprehensive conception of the good since adoption of a faith is sometimes viewed as grounding the meaning of a person's entire life. The idea that the appreciation of

> fine music is a valuable human activity is likely to constitute only a partial conception of the good. Aesthetic appreciation is a possible component in a good life but it does not constitute a full account of the good life. (p. 529, fn 2)

Therefore, ideally, a true education would introduce students to as many comprehensive conceptions of the good as are available. Thus, regarding moral justifications for the objectives of scientific literacy, science education should not privilege either a virtue, principled, or utilitarian justification. Likewise, regarding political justifications, science education cannot favour either political liberalism or communitarianism. Rather, science education must recognize each of these versions of moral and political life as viable and must structure the goals of scientific literacy so as to promote each alternative or at least to make the alternatives available to students so as to keep their futures as open as possible. However, science education rightly can take a negative stand against justifications for scientific literacy that are based on partial conceptions of the good. Thus, for example, a justification for the objectives of scientific literacy based only upon their role in securing employment for the individual or economic prosperity for society does not appeal to a comprehensive conception of the good unless it situates employment and economic prosperity within a more thoroughgoing conception of the good life. For example, the employment and the prosperity might be seen to lead to happier, more fulfilling, and more self-directed lives than otherwise would be possible. Alternatively, they might be seen to promote the possibility for fuller communitarian living.

It may seem ironic that science education must be designed upon a liberal footing if it is to support more than a liberal political agenda and to make available for consideration by students more than one version of moral life. This is so because between the versions of political and moral life under consideration, only liberalism takes the view that it cannot uphold one comprehensive version of the good over another. Even communitarian-motivated education, such as sectarian education, if it is to count as education and not indoctrination, must acknowledge and make its students aware of alternative versions of the good. Nothing can count as a true education that deliberately attempts to circumscribe students' futures by trying to keep morally and politically defensible options hidden or, even worse, by trying to denigrate them. This programmatic stance is the proper one for any version of science education vying for our support.

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Chapter 41
Conceptual Change: Analogies Great and Small and the Quest for Coherence

Brian Dunst and Alex Levine

41.1 Introduction

Science enjoys a privileged and unique position in Western culture. One basis for this privilege is the widely held perception that science continually produces progressively more reliable knowledge about the way our world works. The success of any new tool inspires imitators, and so the epistemic success of science has inspired analogies to other processes of epistemic and conceptual growth and change, including those that presumably take place in the developing mind of the human child. Owing to a thread running throughout Thomas S. Kuhn's *Structure of Scientific Revolutions*, psychologists, as well as historians and philosophers of science, have proposed an assortment of theories for modeling conceptual change in both science and childhood over the last half-century. Many of these models assume a robust bidirectional analogy between conceptual change in childhood development and theory change in the history of science. This analogy suggests that the relevant kinds of changes that a child experiences while acquiring and revising her conceptual makeup are sufficiently similar to the relevant kinds of changes that a scientific community undergoes over the course of its historical progression.

Enabled by this analogy, philosophers and historians of science have helped themselves to the work of developmental psychologists, and likewise developmental psychologists have helped themselves to the work of philosophers and historians of science. The fact that, in any given discussion, the analogy is usually drawn in only one direction works to conceal a potentially vicious circularity: if the analogy lends significantly to insights and inferences in one domain (say, in drawing on an

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analogy from research on conceptual change in childhood in devising philosophical accounts of historical theory change in science), while the codomain from which it draws its insights and inferences relies upon an inverse analogical mapping (from the philosophical explanation of historical theory change in science to research on conceptual change in childhood), we may worry whether, after all, all this theorizing amounts to more than mere theoretical circularity.

If we are to ground either of these domains in methodologically acceptable terms, we must examine and justify the hidden assumptions that underlie this apparent reciprocal analogy between theory change in science and conceptual change in development. For instance, we can investigate whether the availability of a particular learning strategy in childhood (or science) suggests its availability in science (or childhood).[1] If no such guarantee can be maintained, reliance on such analogies is surely excessive and mistaken. In this chapter, we will show that there is perhaps a more interesting and less problematic relation between two distinct and specific ways that researchers invoke the concept of analogy: *argument by way of analogy* and reference to *analogical reasoning*. These, we argue, are distinct objects of research, but there may be an inference allowing results from the domain of analogical reasoning to inform and adjudicate the legitimacy of the arguments by analogy to which philosophers, historians of science, and developmental psychologists have helped themselves. If such an inference is possible, it means that the circularity that threatens researchers in both camps may not be a *vicious* circularity after all. In this chapter, we develop the following preliminary hypothesis: both the analogical reasoning that takes place during conceptual change in childhood and the successful arguments from analogy deployed by scientists express a quest shared by many if not all epistemic subjects: the search for coherence.

In our first section, we consider some of the more influential treatments of the relationship between conceptual change in childhood and science in the conceptual change literature, drawing attention to the extent to which both historians of science and cognitive developmental psychologists, though articulating their approaches in different technical vocabulary, have focused on conceptual change as involving not merely a change in *concepts*, but in *conceptions*. The following section turns to models of analogical reasoning of the sort that have struck participants in the conceptual change literature as promising ways of accounting for conceptual change. In our final section, we turn to the *motives* of the epistemic subject (whether child or adult scientist) embarking on the project of conceptual change.

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[1] A fairly straightforward example – one to which we will return later – is whether mechanisms for the adoption of novel conceptions that maximize conceptual coherence and internal consistency in childhood development are necessary or sufficient for the process of scientific theory change. Similarly, we may ask whether the kinds of theoretical "paradigm shifts" that have historically occurred in science constrain the types of conceptual mechanisms that can allow for successful conceptual change in development. Stella Vosniadou and her colleagues have done extensive empirical research on these issues (cf., e.g., Vosniadou 2007; Christou and Vosniadou 2005; Vosniadou et al. 2004).

41.2 Conceptual Change as Change in Conception

As one of us has argued elsewhere (Levine 2000), Kuhn considered his early work on theory change in science to be deeply resonant with developmental psychologist Jean Piaget's genetic epistemology. For his part, Piaget saw his stage theory of genetic epistemology as attempting "to explain knowledge, and in particular scientific knowledge, on the basis of its history, its sociogenesis, and especially the psychological origins of the notions and operations upon which it is based" (Piaget 1970, p. 1). Thus, Piaget too understood his own hypotheses on childhood development as deriving at least partially from an analogy to the ways in which scientific knowledge changes historically. One can then wonder to what extent the analogy to childhood development that Kuhn meant as a support for his wider position on scientific revolutions – and through which he reasoned in formulating this position – is ultimately rooted in Piaget's intuitions about scientific revolutions. The worry is that Kuhn's appeal to the developmental analogy might be nothing but an appeal to intuition, which would weaken his arguments substantially.

Kuhn's arguments may be salvaged if the analogy runs unidirectionally (viz., from childhood development to scientific theory change, but not vice versa). As Kitcher (1988) observes, the conceptual tools forged during childhood development are available for adult scientists in their theoretical (re)conceptualizations during scientific revolutions (as well as normal science); but it is less plausible that highly nuanced and complex scientific theories are available conceptual resources for developing children. Intuitively, this places developmental psychology as *epistemically* prior to the study of historical scientific change. Unfortunately for Kuhn, while many developmental psychologists may agree with this order of epistemic priority, Piaget did not – and Kuhn himself appears to have realized this. In a telling footnote in *Structure of Scientific Revolutions*, Kuhn approvingly cites Piaget's historical sensitivity: "Because they displayed concepts and processes that also emerge directly from the history of science, two sets of Piaget's investigations proved particularly important" (Kuhn 1996, p. vii). Presumably, Kuhn believed that the close relationship that Piaget saw between childhood development and theory change throughout the history of science was evidence in support of his own thesis. The two approaches likely appeared to Kuhn as mutually reinforcing and suggestive of a more broadly *coherent* theoretical picture – which itself would have lent itself to the plausibility of Kuhn's philosophical project.

For our purposes, a paradigm case of an account that addresses the relationship between Kuhnian scientific concept change and (psychological) conceptual change in individual agents may be found in Posner, Strike, Hewson, and Gertzog's 1982 paper, "Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change." In it the authors construct their account to show how individual proto-scientists go about making radical changes in their central or "core" concepts (e.g., going from thinking of physics in terms of Newtonian mechanics to thinking in terms of Einsteinian relativity), but without revising more mundane or peripheral concepts and beliefs (such as the belief that it is in fact not raining outside right now). Thus, their argument points toward the now familiar differences between (mere) concepts and (full) conceptions. Briefly, a *concept* is one node within a conceptual framework, and a *conception* is the relatively modular constellation or web of relations that define a particular knowledge domain. "Force" is a concept within a "Newtonian Mechanical" conception of physics. Posner and colleagues rely heavily on the legitimacy of an analogy drawn *from* Kuhnian scientific change literature *to* the psychological processes involved in scientific learning.

Their use of this analogy is unidirectional. They wish to show that the processes involved in Kuhnian paradigm shifts from normal science, through a scientific revolution, and into a new paradigm *are of the same kind as* those taking place within novice students of science. Initially they draw the analogy between the kinds of process involved both in historical episodes of concept change and individual episodes of scientific learning – both are processes requiring changes to be made to "core" concepts. A "core" concept is one whose character is in some causal way determinant of an entire conception. Change a "core" concept and the result is that the entire conception is qualitatively affected.

Here Posner and colleagues appropriate Imre Lakatos's distinction between the *assimilation* of "recalcitrant" (anomalous) data by making changes to the "protective belt" of auxiliary hypotheses, methodologies, and beliefs and *accommodation* of the "research program" (including making changes to its "hard core") to the recalcitrant data. In the former (assimilation), current theoretical commitments, methodologies, and scientific practices provide the "background" upon which new concepts are to be understood. If the new concepts can be reconciled in a way harmonious with these background commitments, the new concept can become accepted into the general theoretical framework of the research program without any radical revision. In the latter (accommodation), the new concept cannot be reconciled with the background commitments harmoniously, and the new concept either poses a threat to the very identity or "hard core" of the research program or is dismissed as observational error. Posner and collaborators make analogical use of "assimilation" and "accommodation" in their account of scientific learning. Learners "assimilate" by using their current conceptual commitments as a basis or background in assessing new phenomena or concepts. When the new phenomena or concepts resist cohering with background conceptual commitments, they must instead be "accommodated."

Piaget (1953) also prominently features the concepts of assimilation and accommodation in his theory of genetic epistemology. For Piaget, the processes of assimilation and accommodation form a dialectically coupled adaptive system. An attempt at assimilation is an attempt to fit one's occurrent state of affairs to one's occurrent belief system. Piaget likened successful assimilation to successful biological adaptation. When assimilation fails as an adaptive mechanism or strategy, learners must attempt accommodation – changing their occurrent belief structure to fit with the occurrent state of affairs. Importantly, Piaget saw *both* processes of assimilation and accommodation as necessarily altering one's conceptual structure. Thus, any assimilation necessarily requires *some* accommodation, and any accommodation is accompanied by assimilation. This would seem to contrast with the Posner group's usage of "accommodation," unless we understand their emphasis as a matter of degree: the sense in which they use the term accommodation is said to occur only under conditions of radical revision in conceptual structure.

Borrowing from Stephen Toulmin (1972), Posner and colleagues refer to the causal interdependence between one's concepts and conceptions as one's "conceptual ecology." The issue central in their discussion is identifying the conditions and features of conceptual ecologies under which scientific learners come to *accommodate* new core concepts. Toward this end, they outline four primary conditions severally necessary and jointly sufficient for accommodation to occur:

1. There must be dissatisfaction with existing conceptions.
2. A new conception must be intelligible.
3. A new conception must appear initially plausible.
4. A new concept should suggest the possibility of a fruitful research program. (Posner et al. 1982, p. 214)

It should be clear that these conditions are meant to align to similar Kuhnian conditions for adopting a new scientific paradigm. These conditions would look something like the following:

1. There must be dissatisfaction with the existing theoretical scientific framework(s).
2. A new scientific paradigm must be intelligible.
3. A new scientific paradigm must appear initially plausible
4. A new scientific paradigm should suggest the possibility of a fruitful research program.

Each of these four conditions needs to be met in order for a new theoretical paradigm to be taken up by a scientific community. Kuhn famously belabored how difficult it is for a single person to bridge the divide between two paradigms. However, if Posner and colleagues' analogy is to hold, this is precisely what occurs in the process of conceptual accommodation. Drawing directly from Kuhn's arguments, Strike and Posner later argue that – for similar reasons – changes to one's scientific conceptions, or to core concepts, are likewise difficult: "If one assumes that misconceptions are similar to paradigms, these views provide obvious reasons why misconceptions will be resistant to change, even given contrary instruction" (Strike and Posner 1992, p. 153). This is one reason, they say, that explains why established misconceptions are so robust and persistent in the context of science learning.

Posner and colleagues identify other constraints that keep learners from assimilating (and thus push toward accommodation). These constraints are features of the learner's conceptual ecology that are particularly influential in deciding which concepts come across to the learner as the most plausible. Thus, their model of conceptual succession is recursive: the character of the current conceptual ecology casually influences or determines the successor conceptual ecology. In the case of core concept change, this means that there are conceptual ecological factors that constitutively factor into shaping the character of the new (successor) core concept(s).

There are two assumptions worth mentioning about the kind of learners that Posner and colleagues are talking about here: first, they are rational. The decision procedure involved in their account of core concept change depends on the learner's being capable of rationally weighing the evidence and choosing the best alternative on well-reasoned grounds. Thus, the authors assume with Allison Gopnik that science learners are already "little scientists." The second assumption is that conceptual knowledge is essentially representational. Elsewhere (Levine and Schwarz 1993; Brooks 1991), both of these assumptions have been problematized, but it is worth noting that the view Posner's group put forth is fundamentally tied to them.

With this in mind, the remaining conceptual ecology constraints are the character of the anomalies affecting current concepts, analogies, and metaphors used to make novel concepts intelligible; epistemological commitments such as current explanatory ideals and views about the character of knowledge; the metaphysical beliefs and concepts that make sense within the current conceptual ecology, whether knowledge in other fields coheres with new concepts; and the character of concepts in competition for accommodation. Given these myriad conflicting constraints, concept change is difficult. Whenever possible, learners will attempt to assimilate rather than accommodate new concepts. Only when assimilation doesn't work does accommodation become a practical possibility – and only when a novel concept can be seen as intelligible does accommodation become a plausible action.

Just as Kuhn later qualified his claims about incommensurability, Posner and colleagues qualify their claims about the processes involved with accommodation. Specifically, they preserve the possibility of partial accommodation, in which the process of accommodation is not a binary, all-or-none affair. This means that for any given conceptual core, there may be unresolved inconsistencies or incomplete explanations. It follows that accommodation needn't be abrupt. It may take some time to make all the revisions necessary to move from a change in core *concept* to a change in overall *conception*. Given the number of causal variables and interactions in a conceptual ecology, the process of accommodation will also most likely be nonlinear and involve a process of trial and error and revision in order to cohere the core and peripheral concepts of a conception.

All of these qualifications fit nicely with Kuhn's later (1970) amendments to his account of theory change in scientific communities wherein he makes room for external beliefs and values in playing a (nonlinear) causal role in the processes of theory adoption. As is now well known, Kuhn's later views downplayed radical incommensurability, which in turn opened the door for closer analogies between scientific practice and developmental psychology (cf., Hoyningen-Huene 1993; Levine 2000). There is no question that Posner and colleagues' account of core concept change as the causal inter-workings of a learner's conceptual ecology draws a strong analogy from the Kuhnian literature. Strike and Posner later write:

> We have been substantially influenced by those theories of rationality that have been developed by authors such as Kuhn, Toulmin, and Lakatos…the substantive conceptions (of Kuhn's paradigms and Lakatos' research programmes) suggest what are to count as problems and what is to count as relevant evidence. Indeed, they provide the perceptual categories by which the world is perceived…Such accounts of rationality can be easily turned into accounts of rational learning suitable for pedagogical purposes. (Strike and Posner 1992, pp. 151–2)

While Strike's and Posner's optimism is commendable, and their utilization of the general Kuhnian framework is interesting and fruitful as a research program, what remains to be seen is whether such a strong analogy is warranted. Are the kinds of learning experiences science learners undergo sufficiently like historical changes in scientific communities? In order to assess this question, we would do well to understand exactly what features are meant to be analogous and which aren't. And to do this, we must first get clear on the kind of relationship an analogy conveys.

41.3 Analogy

For the purposes of this chapter, we will be utilizing a variant of the Structure-Mapping approach to analogical reasoning originally developed by Dedre Gentner (1983). This approach employs a basic distinction between what it calls "source" and "target" domains. In discussing conceptual change in childhood or science, the domains are typically supposed to be conceptions or theories, together with modes of conceptual or theoretical change.[2] For ease of exposition, we will be employing the term "theory" to represent both scientific theories, as well as conceptions. The presumed analogy between theories operates as a functional mapping from the source domain to the target domain. Typically, the source domain is taken to constitute a more reliable object of knowledge than the target domain. These analogical mappings can accommodate different degrees of structural stringency. The strongest mapping, and upper bound, for stringency in an analogy is identity between source and target domains. If the domains are *identical*, the mapping is not appropriately called an analogy (rather, it is an endomorphism – a mapping from a domain back to itself). Short of identity, the next most stringent class of mappings is *isomorphisms*, mappings that maintain source domain relations among elements of the target domain.

Less stringent are *homomorphic mappings* for which the mapping function defines a transformation wherein some, but not all, of the relational structure is maintained. There are at least two interesting kinds of homomorphic structural mappings: those whose domains *differ in kind* and those whose domains *differ in degree*. In a homomorphic mapping between different kinds, the source and target domains

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[2] This presupposition is typical of, though not exclusive to, "theory-theory" approaches to the developmental attainment of conceptual tools for dealing with human behavior, where the theory most children acquire is variously called "folk psychology" or "theory of mind." In such contexts, the debt owed to the history and philosophy of science is often explicitly acknowledged, as in the title of Piaget student Annette Karmiloff-Smith's (1988) essay, "The Child is a Theoretician, not an Inductivist." In another example, Allison Gopnik observed that the tendency of developmental psychologists to refer to a child's conceptual knowledge base as a "theory" is a reflection of the extent to which developmental psychology must be previously informed by the history of science. She writes (1996): "cognitive and developmental psychologists have *invoked the analogy of science itself*. They talk about our everyday conceptions of the world as implicit and intuitive theories, and about changes in those conceptions as theory changes" (Gopnik 1996, p. 485, emphasis added).

are taken to be independent knowledge stores. There are very few if any recognizable entities common to both source and target domains. Homomorphic mappings between domains that differ in degree are taken to draw from one conceptual knowledge store but in ways that preclude identity (allowing us to consider the source and target domains as effectively distinct).

A good example of an analogy whose source and target domains differ only in degree is Darwin's argument by analogy in *The Origin of Species*. There are two analogies that comprise the backbone of Darwin's argument. First is his analogy for the mechanism of evolution. He draws from the source domain of "artificial" selection (animal husbandry) whose effects were well known and documented to the target domain of "natural" selection which was to work via the very same functional mechanisms (selective retention of favorable characteristics) as artificial selection. The identity of the underlying mechanism of change in both domains (selection) suggests the difference between them is merely one of degree. What differs is the amount of time required for the phenotypic effects of either process to noticeably accrue and the physical means by which selective retention operates (human breeders selecting breeding pairs in artificial selection and random mutation and the "struggle for existence" in natural selection). Darwin applies a second analogy between the conventional taxonomic units *species* and *variety*. He argues by way of analogy that different varieties differ from each other just as different species differ from each other – that is, the differences (all around) are *of a* kind (not *in* kind). The only *difference* between variety-difference and species-difference is in the degree of phenotypic divergence. As Darwin puts it, "a well-marked variety may be justly called an incipient species" (Darwin 1859, p. 52).

Even less stringent than homomorphic mappings are *congruence relations*, which do not provide well-defined transformative functions directly between source and target domains, but for which an intermediate domain can be constructed. A pair of homomorphisms can then be given defining transformations from source to intermediate and from intermediate to target domains. Important in congruence relations is that transitivity strictly cannot be maintained through both transformations (viz., from source, through the intermediate, to the target domain). We will call the intermediate domain the *transfer domain*. The limiting case of analogical mapping is *disanalogy*, wherein there is no readily apparent congruence relation.

For present purposes, this taxonomy of analogies will serve two distinct but related functions. First, it will help us to get clear on the nature of the often invoked if seldom scrutinized analogy between conceptual change in science and conceptual change in childhood. Different sorts of analogy support different sorts of inference. If we suppose that the two domains of conceptual change are isomorphic, the analogy between cognitive development and the history of science ought in principle to support inferences in both directions with the risks outlined above. If, on the other hand, they are connected only by congruence relations, such risks are mitigated – but then arguments that invoke such an analogy carry significantly less weight than often assumed.

But our discussion of analogy serves a second purpose. Recognition of the prevalence and significance in the conceptual change literature, of an analogy between conceptual change in childhood and conceptual change in science, led us to consider the role of *argument* by analogy in general. Confusing matters is that within that same literature, processes such as *argument from analogy* and *analogical reasoning* have also been touted as playing central roles in the actual cognitive processes of conceptual change. Let us assume, for the moment, that whatever the precise nature analogy between childhood development and scientific change, it is close enough to allow us to treat argument from analogy *as a species of* analogical reasoning (Gentner 1983). In that case, the precise entailments of this analogy may well be illuminated by an account of the role of analogical reasoning in conceptual change. That is, by getting clearer on the ways in which analogical reasoning functions, we will be in a position to better understand whether arguments by analogy relating conceptual change in science and childhood development are as problematic as they seem.

Analogical reasoning is often used in mapping congruently related conceptual domains and, for the purposes of analysis, often requires carefully constructing a transfer domain. But how are transfer domains constructed? Or, to address our specific concerns more directly, how can a novel theory be discovered, developed, or changed? Many commentators (notably Susan Carey) think it is reasonable to suppose that this task necessitates some sort of "bootstrapping" process imaginatively drawing upon available cognitive resources. As we have seen, Posner and colleagues require that successor core concepts causally depend on the current state of one's conceptual ecology. There are many accounts of the possibilities and constraints constitutive of such available resources, though the proper exposition of even the most plausible of these theories is far too ambitious for the scope of this discussion (see instead, e.g., Carey 2009 and Strike and Posner 1992). Additionally, we may wonder whether the necessary bootstrapping process is systematic enough to give rise to what might plausibly be called a theory. It would be enough, for starters, to articulate a theory of analogical reasoning consistent with the constraints operating in any one of the domains of conceptual change, if not all of them at once.

As an example of the construction of a transfer domain, we consider an idealized analogy between the solar system and the atom, as Ernest Rutherford would come to understand it. For our source domain, we select the solar system as described by Newtonian mechanics. Presumably, we are constructing an analogy between the solar system (source domain) and the atom (target domain) in order to explain or understand some aspect of the atom that has previously escaped our grasp (viz., the experimental evidence that it is composed mostly of empty space). In such cases, an analogical transfer domain can be used as a cognitive resource to model the relevant aspects of the target domain. It should be noted that the reason we use the solar system–atom analogy as an example of a congruence mapping (rather than the stronger homomorphic mapping) is because much of the relational structure is not maintained between the two models. Electrons possess substantially different properties and behave in drastically different ways from planets in their orbits about the Sun. Since the analogical relation is more metaphorical than literal, we are put in a position of needing to "spell out" more precisely how the analogy is to work. To do this, we draw an intermediate analogy to some other domain that helps clarify the analogical relation in both domains. In general, the need for a transfer mapping is indicative of a congruence analogy for the precise reason that the difficulty or impossibility of an adequate direct mapping precludes a homomorphic approach.

Through a process of abstraction, we can compile a set of comparable attributes between the source and target domains. This set will comprise the transfer domain. First, let us state the source and target domains:

(S): The solar system contains less massive planets that centripetally orbit a more massive Sun, with most of the volume of the solar system occupied by empty space.

(A): The atom is comprised of constituents similar in various ways to positively and negatively charged particles (α and β particles) recently observed. The whole is largely transparent to energetic α particles (see Geiger and Marsden 1909; Rutherford 1911) and must thus be mostly empty.

We have purposefully worded these two descriptions so as to easily lend themselves to common abstraction. In vivo, the process of honing the language used for comparison would likely be a more complex process involving multiple steps, each utilizing analogical reasoning. One can imagine a child (or scientific community) working through a series of partial, transient, provisional, and defeasible analogical reasoning processes in order to formulate the *source* domain of a more general transfer mapping. Finding an effective transfer domain is likely a hard-won victory. Additionally, there may be many alternative abstractive partitionings of specific contexts or problem situations for each of (S) and (A). Our task is to create one, (T), for which we can simultaneously define homomorphic mapping functions from (S) to (T) and from (T) to (A). There needn't be one and only one mapping of this kind. It stands to reason that with a greater number of potential mappings comes increased likelihood of the successful construction of a transfer domain – as an increase in potential mappings corresponds to an increase in available cognitive resources (such as concepts, conceptions, and conceptual relations, among others). For the sake of this example, we now provide one such transfer domain:

(T): The model contains entities that orbit a central object, bound by an attractive force exerted from the central object on the orbiting entities.

We are now able to construct a pair of homomorphic mappings (analogies): one abstraction from (S) to (T) and one instantiation from (T) to (A). So long as we succeed at constructing such mappings, we are guaranteed to meet certain relevancy criteria – in fact, the transfer model itself functions as a minimal relevancy constraint for the analogical task.

Now that each of the source and target model can be expressed in terms of the abstract transfer model, we have grounds for inductive hypothesis testing to help determine whether the relevancy constraint established by the transfer domain survives further observation. By discovering relevant similarities and dissimilarities through this process, we have assembled a procedure by which we can come to understand the target domain better. The point is just that such analogical comparison establishes a mechanism for generating testable hypotheses. More generally, such a process of mapping from a source conception to a transfer conception and then again from the transfer conception to a target conception allows for a learner to make the requisite transition from one conceptual ecology to a new one – or to shift from a misconception to a correct conception. A larger worry remains with the question as to whether analogical transfer mappings are *actually employed* by children or scientific communities in vivo. Nancy Nersessian has argued that in at least some contexts of scientific modeling, this does occur (Nersessian 2008, pp. 206–207). However, it remains less obvious that childhood conceptual development employs such a mechanism.

Gentner and Markman have devoted significant attention to the structures and relations that impose psychological constraints on analogical reasoning. In particular, they understand analogy as dependent on our psychological abilities to "align" or to bring into attunement the basic structures (or gestalts) of the domains involved in the attempted analogy (Gentner and Markman 1997). They identify three specific psychological constraints on analogical reasoning:

1. *Structural consistency*: It must observe parallel connectivity and one-to-one correspondence. Parallel connectivity requires that matching relations must have matching arguments. One-to-one correspondence limits any element in one representation to at most one matching element in the other representation.
2. *Relational focus*: Analogies must involve common relations but need not involve common object descriptions.
3. *Systematicity*: Analogies tend to match connected systems of relations. The systematicity principle captures a tacit preference for coherence and causal predictive power in analogical processing. (Gentner and Markman 1997)

Important for Gentner and Markman are not only the *similarities* in structures but the *differences* as well – both similarities and differences are alignable. They understand analogical reasoning to involve an iterable process of connecting one domain to another. On the taxonomy we have developed here, what is interesting in Gentner's and Markman's "structural alignment framework" is that it implies that through the processes of analogical reasoning, we can *massively* and *in parallel* employ multiple *transfer mappings* in an iterable fashion – one transfer mapping after another, connected in serial. Presumably, the only stop to such a process occurs when some psychological state of relative equilibrium is reached. The question that remains is what the conditions for such equilibrium could be (i.e., *in what* is there equilibrium? External coherence? Internal consistency? Practical applicability?)

Susan Carey, for her part, writes extensively on the kinds of mechanisms required to satisfy what she believes are the constraints on childhood learning. For her, an innate conceptual core in conjunction with a "Quinean bootstrapping" process that incorporates available external resources is necessary for the possibility of coming to understand the kinds of complex scientific theories that members of our scientific communities clearly require. Carey is concerned with the conditions and constraints operative in cognitive development that allow (or in some cases prohibit) an agent to come to understand, for example, continuous rather than discrete conceptions of number. Such "theoretical" understandings underwrite the more complex scientific theories that utilize and employ them. So for Carey, theory development and construction always recursively operate on current cognitive resources, which include an agent's prior theoretical attainments, a mode of communication capable of translating from a standing theory (source) to a novel one (target), as well as physically and socially available resources (e.g., external tools for learning, teachers). In many cases, the "novel" theory is not truly novel in that it is included in some of the available resources; for example, teachers already possess a solid understanding of the target theoretical domain (cf., Carey 2009, pp. 413–445).

Crucial to Carey's and others' formulations of theory change is that incommensurability is always local. Largely in response to criticisms of *structure*, the later Kuhn came to think of theory incommensurability as analogous to localized problems of translatability between languages, in contradistinction to his early claims of global incommensurability (roughly analogous to Quinean radical indeterminacy of translation). Carey's "Quinean bootstrapping" process precludes global incommensurability and untranslatability in that more basic concepts, theories, language use, and practices remain relatively unaffected by specific theoretical alterations. For example, in the midst of a conceptual theory change from discrete to continuous number theories, a child's beliefs and theoretical understanding about colors may be unaffected at first. It is possible that a theoretical conceptual change causes a cognitive agent's understanding to undergo global change – but not all at once. Eventually, the child may come to understand difference in hue as a continuous difference, but perhaps not, and perhaps not at first. Carey is at pains to emphasize that the process of Quinean bootstrapping (and the associated conceptual change it enacts) is difficult, often incomplete, and takes a lot of time.

An alternative approach toward the dynamics and constraints involved in conceptual change is the "Multiple-Interaction" approach discussed by Nira Granott (1993). She suggests that highly important to factors formative in a learner's conceptual development are the kinds of social contexts and interactions fostered and engaged in by both novices and experts. Instead of referring to individual and isolated psychological processes, Granott proposes that analysis should reflect the *social* etiology of cognitive processes. Her model differentiates (as a matter of degree) first between collaborative and disruptive interactions. Second, she tracks the degrees and types of expertise involved in interactions and the degrees of involvement of each participant. Some of the categories involved in her multidimensional analysis include *mutual collaboration* between equal peers; *symmetric counterpoint* relationships between interactants who take varying approaches to solving the same problem; *parallel activity*, in which individuals attempt to solve a problem in a relatively isolated (but coordinated) way; *asymmetric collaborations* between novices and experts; and *asymmetric counterpoint* relationships between novices and experts. Granott acknowledges that such relationships may also turn disruptive and that there are myriad other social factors that affect conceptual development (such as expertise in irrelevant domains, social roles, gender, race, personal histories of previous interactions, dynamic personality traits). But the general point is that perhaps Quinean bootstrapping is not the only factor required in conceptual development or at least that it shouldn't be focused on to the exclusion of other social factors.

41.4 Coherence

Our discussion thus far has pointed to the significance of conceptual change not as a change in concepts but as a change in *conceptions*. Such change, we have argued, involves the construction of mappings across conceptual domains. We have yet to consider the epistemic subject's *motives* for constructing such mappings. With this third piece in place, we will finally be in a position to articulate the hypothesis we advertised at the beginning of this chapter concerning the relationship between conceptual change in childhood and science: both express the epistemic subject's quest for coherence.

In a well-known discussion, Paul Thagard has argued that in conceptual change, cognitive agents are often motivated by a need to cohere all theoretical beliefs. He defines, and for the purposes of this chapter, we follow him in defining, the notion of conceptual coherence as follows:

1. Conceptual coherence is a symmetric relation between the pairs of concepts.
2. A concept coheres with another concept if they are positively associated, i.e., if there are objects to which they both apply.
3. The applicability of a concept to an object may be given perceptually or by some other reliable source.
4. A concept incoheres with another concept, if they are negatively associated, i.e., if an object falling under one concept tends not to fall under the other concept.
5. The applicability of a concept to an object depends on the applicability of other concepts (Thagard 1992; Thagard et al. 2002; Thagard and Verbeurgt 1998).

Reconsidering the example of the transformation of color conceptions discussed previously, Thagard's notion of conceptual coherence (and incoherence) suggests that the developing agent's naïve theory of color was incommensurable (or "incoheres") with a new understanding of continuity in number as well as with phenomenal and empirical evidence (perhaps from recently seeing a rainbow and its continuous blending of hues). Kuhnian historians of science, as well as more recent contributors to cognitive developmental psychology, might see such motives at work in participants in the "crises" that accompany scientific revolutions. To Thagard, what makes a crisis is that incoherence appears as problematic for us both as individual subjects and as members of scientific communities – conceptual incoherence is something that begs for remedy. In this, way we may finally see an anchor for an appropriate transfer domain in a useful analogy between concept change in childhood development and theory change in scientific communities: in both cases, the primary motivation is to cohere our understanding about the world. We might understand this drive toward coherence as underwriting scientific methodology as well as childhood curiosity or even as the primary underlying thread in analogical reasoning – especially in congruence mappings necessitating the utilization of a transfer domain. The institutionalization of scientific practice is nothing over and above the value that each of its communities' members places on coherence. This valuation of coherence by each member of a scientific community is no different *in kind* from the importance attached to coherence by a curious child. If there is a difference between these two, it is of *degree* or in the mode of implementation; and the analogy between them remains strong. If there is no difference, the analogy collapses into an identity – the claim that children are engaged in precisely the same coherence-resolving activities as adult members of scientific communities.

Considered from the vantage point of research in conceptual change, learning scientific concepts is often understood as replacing one's state of confusion, misconception, or overly simplistic or "common sense" understanding of a knowledge domain with more complex or theoretically sophisticated newer models. Strike and Posner (1992), for example, regard the replacement process as necessarily involving cognitive dissonance between actively conflicting conceptions. Generally, such conceptual change is understood as the comprehensive replacement of entire conceptions within a particular knowledge domain, rather than the piecemeal replacement of individual concepts within an overall conceptual or theoretical structure whose structure is preserved (cf., e.g., Vosniadou and Brewer 1992; Carey 1985; Chi 1992; diSessa 1988; Posner et al. 1982). Such a conceptual structure is thought to undergo a process of holistic reorganization until a stable or consistent set of interrelated and more scientific conceptions is attained. Again, Strike and Posner (1992) see this process as a decision (of sorts) between competing conceptions – one of which provides a more intelligible, coherent, plausible, and fecund outlook for the knowledge domain than the alternatives.

More recently, there has been substantial debate about the extent to which conceptual change in childhood succeeds at fulfilling the conditions of intelligibility, coherence, plausibility, and fecundity. As recently canvassed by Rusanen and colleagues (2008), "There is [now] a large body of experimentally based literature where it has been argued that the difference between the consistency or coherence of the belief systems of novices and experts is one of degree, not of kind" (Rusanen et al. 2008, p. 65; cf., e.g., Vosniadou 2007; Christou and Vosniadou 2005; Vosniadou et al. 2004). Some researchers, for instance, have proposed that novice "explanatory frameworks" are themselves already internally coherent, consistent, and interrelated sets of beliefs in a sense evocative of Kuhnian "Paradigms" (Samarapungavan and Wiers 1997). Others, such as Chi and her colleagues, have argued that novice belief systems exhibit "ontological" conceptual coherence (Chi 1992; Chi and Slotta 1993; Slotta and Joram 1995). Alternatively, there are also those who disagree with these characterizations of novices' belief systems. Andrea diSessa (1993) and Smith et al. (1994), for instance, describe novice learning as relying not on coherent, systematic theories but rather as more or less unorganized, context-sensitive elements belief-like primitives that are systemically inconsistent and thus do not cohere. In diSessa's "knowledge-in-pieces" account, naïve physical knowledge is organized into phenomenological primitives or "p-prims" – a novice's simple explanations abstracted from experiences and uncritically accepted (diSessa 1983).[3]

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[3] We are grateful to Anna-Mari Rusanen for pointing us toward many of the works cited in this paragraph.

There is much to be said about whether and to what extent the value of coherence is socially inculcated (perhaps as a resource for Quinean bootstrapping of concept change) during childhood development. But our discussion has perhaps more clearly shown that as a matter of both causal influence and epistemic priority, the relation between childhood development and historical theory change in science is something of a chicken-and-egg problem. One cannot be resolved without necessary reference to the other. If there is something, then, that underwrites the analogy between the two, it is that both developing children and scientific communities share the (perhaps often implicit) underlying valuing of coherence, which acts to regulate the quest for knowledge. So, while the particular material and conceptual resources available to developing children on the one hand (e.g., social and cultural educational tools, practices, and resources) and adult members of a scientific community (e.g., the institutions and the tools and practices deployed scientific research) on the other are clearly distinct and different from each other, the underlying coherence-seeking processes by which each domain operates contribute to genetically informing and reinforcing the same process in the other. Thus, this relationship between Kuhnian theory change in the history of science and developmental conceptual changes in children should perhaps not be seen or understood as an *argument by analogy* as much as a complex causal interrelationship in which both domains materially depend on *analogical reasoning*. Along with hosts of other cognitive and methodological resources, these analogical reasoning methods causally factor into and influence the relations that genetically inform and reinforce particular epistemic developments in both developing children and adult scientists.

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Chapter 42
Inquiry Teaching and Learning: Philosophical Considerations

Gregory J. Kelly

> *Indeed, the very word 'cognition' acquires meaning only in connection with a thought collective.*
>
> Ludwik Fleck 1935

42.1 Inquiry in Science Education Reform

Debates regarding science education go through various stages of reform, perceived change, and more reform (DeBoer 1991). These changes have centered on the extent to which students' interests, autonomy, and knowledge are balanced against the cultural knowledge of the legitimizing institutions. Dewey (1938a), Schwab (1960), Rutherford (1964), and more recently the (USA) National Research Council [NRC] (1996, 2011) have, in various ways, called for engaging students in the scientific practices of professional scientists. These calls for reform conceptualize inquiry differently, and each can be viewed as making a set of assumptions about knowledge, science, students, and learning – thus suggesting the need for examining epistemological issues in science teaching and learning. In this chapter I consider some of the opportunities afforded by an inquiry-oriented science education but also the constraints to successful implementation of inquiry in schooling.

Inquiry in science entails conducting an investigation into the natural or designed world, or even into the applications of scientific knowledge to societal issues. Such investigations typically concern a domain for which at least some of the participating inquirers do not know the results prior to the investigation. Dewey (1929, 1938a) characterized inquiry as dialectical processes emerging from problematic situations

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aimed at reaching some resolution.[1] Inquiry has been characterized as engaging learners in scientifically oriented questions, formulating and evaluating evidence and explanations, and communicating results (National Research Council 1996). As such, inquiry is derived from views of knowledge, is underwritten by interpretations of knowledge, and instantiates perspectives on knowledge. Furthermore, the referent for what counts as inquiry activity need not be limited to the work of professional scientists, as other members of society can be viewed as engaging in scientific practices. Thus, inquiry science poses epistemological questions, and with a focus on science education, these questions can be addressed from a philosophy of science point of view.

Interesting questions arise as to whether inquiry science teaching is directed at learning knowledge and practices of science or at aspects of the nature of science or both. We can speak of learning science through inquiry, where inquiry is the means to learn knowledge and practice. Or we can view the pedagogy as inquiry about science where the intent is to communicate lessons about the nature of science. Often these perspectives on inquiry purposefully brought together, so that learning knowledge and practices through inquiry serves to inform students about science by engaging in the practices constituting scientific activity. I will refer to the dual purpose approach as teaching science as inquiry. As each of these views of inquiry presupposes views of scientific knowledge and thus manifests an epistemological orientation, we would expect to find implications of the philosophy of science for teaching science in this manner. Nevertheless, the relationship of inquiry teaching and philosophy of science is not straightforward.

42.2 Educational Challenges of Teaching Science as Inquiry

There are a number of important challenges to teaching science as inquiry. First, through many years of research and across different learning theories, it is clear that students need concepts to learn concepts. Students learn concepts in bunches, and these cannot be typically investigated one at time through (even careful) classroom-based practice activities or empirical investigations. Educators should not assume that students are able to induce sophisticated scientific concepts from empirical phenomena. While few educational programs explicitly assert that students construct knowledge in the absence of more knowing others, a number of perspectives suffer from this assumption, often under various banners such as hands-on learning, discovery, or radical constructivism (Kelly 1997). As some knowledge is required to learn, then inquiry approaches that situate the student at the center of investigation need to recognize that only with sufficient, relevant background knowledge can answerable questions be posed by students. Thus, inquiry approaches to science

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[1] Dewey's (1938a) definition is as follows: "Inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole" (pp. 104–105).

learning need to consider the importance of learning through engaging in activities and discourse of science with more knowing others.

A second challenge for inquiry instruction is that learning science entails more than learning the final-form knowledge of scientific communities (Schwab 1960; Duschl 1990). While propositional knowledge (*knowing that*) is important, knowing how to engage in scientific practices and how to make epistemic judgments ought not be neglected. Therefore, science learning should include conceptual, epistemic, and social goals (Duschl 2008; Kelly 2008). While much of inquiry has focused on students' engagement in practical or laboratory activities, pedagogies focused on socioscientific issues and science in social contexts pose important opportunities to learn through investigations in unknown domains (Sadler and Fowler 2006). Inquiry can arguably include evaluation of expertise, certainty, and reliability of scientific claims of others.

A third challenge to learning science as inquiry concerns the nature of the intended propositional or procedural knowledge (*knowing how*) in the curriculum. Science topics and community practices may be more or less appropriate for an inquiry approach. Some knowledge and practices may be attainable through student-centered approaches, while others require the direction of more knowing others. Clearly, at least some scientific practices can be learned only through intensive effort, which may require extensive participation in a community of learners. Other topics might be suited for other forms of instruction. Furthermore, methods of assessment, either formative or summative, need to be carefully chosen to match the learning goals appropriate to the knowledge sought.

Fourth, learning the conceptual knowledge, epistemic criteria, and social practices over time in science domains may require coordination of scope vertically (across grades over time) and horizontally (across subject matter areas at a given grade) across the curriculum. While academics find ways to separate disciplines, and there may be interesting epistemological distinctions, students experience schooling as a whole. Science may not be separate from views and knowledge of history, mathematics, reading, writing, and so forth. Thus, the challenge for teaching science as inquiry includes understanding how such approaches can be supported or undermined by other curricular decisions and pedagogies, both from within and from outside science programs.

Despite these challenges, inquiry teaching and learning have been advocated in different forms many times across generations (most recently, see NRC 2011). The potential for learning knowledge and practices of disciplines through engagement in purposeful activity has been recognized both as a means to learn science and as a way to develop student interest. The linguistic turn in philosophy and the continual rediscovery of the importance of learning through participation in discourse practices of epistemic communities have led educators to examine ways that inquiry can be enacted in various settings. This potential of engaging in discourse practices as inquiry has not always been realized, and there is still considerable debate about the nature of inquiry and its overall merits (Blanchard et al. 2010; Kirschner et al. 2006; Kuhn 2007; Minner et al. 2010). Much of the debate fails to recognize the relationship and disagreement among the learning goals, limited measures of assessment, and the purposes of education – that is, rhetorically, the interlocutors argue past each other. Much of this debate regarding differences in traditional and experiential education was identified in Dewey's (1938b) *Education and Experience*. Has the field advanced since? How can philosophy of science help? To address these issues, I consider some challenges for using philosophy of science in science education.

42.3 Challenges for Using Philosophy of Science to Inform Inquiry Science Teaching

Just as inquiry poses challenges because of the realities of teaching and learning science, drawing from the philosophy of science to inform science education poses challenges because of the nature of philosophy. Educators have called for developing philosophically informed science curricula (Hodson 2009). While this is a welcome perspective, in this section I examine the assumptions of the application of philosophy of science to science education and note that some of the difficulty lies not with educators' misunderstandings about philosophy but rather with the nature of philosophy as a discipline. I identify four dimensions of this difficulty.

First, the philosophy of science treats a number of technical issues that may not directly inform educational practices. Throughout the history of the philosophy of science, issues such as inference, perception, and abductive reasoning form the basis for a number of technical arguments conducted by specialists. These arguments are important for the development of the field of philosophy of science and may advance understanding about the nature of science, but do not necessarily lend themselves readily to educational applications. For example, one debate concerns arguments for an instrumental versus realist view of scientific theories (van Fraassen 1980; Boyd 1991): Do theories serve as predicting devices or rather do they refer to real objects in the natural world independent of our theory-dependent views of such objects? While there is something at stake in philosophy, and indeed plausibly for education, regarding instrumentalism and realism, the technical arguments do not necessarily lead to specific implications for education. For example, scientific realism and constructive empiricism recognize the strong theory dependence of scientific methods. Procedures and inferences about actions in the course of an investigation are dependent on the extant theoretical knowledge of the inquirers. This level of consensus may be enough to develop science curricula that propose reasonably informed experiences for students, without a final answer to the instrumentalist-realist debates. While the particulars of the debate may not have easy answers for education, there are useful tools and ways of thinking in philosophy of science that have merit for education.

Second, philosophy of science includes different perspectives and knowledge that change over time. As philosophy of science changes, educators need to work to understand those changes and update their own of philosophies of science. Furthermore, this effort will be complicated by the number of philosophical positions. For example, Laudan (1990) broadly identifies four major research traditions: positivist, realist, relativist, and pragmatist. Within any one of these perspectives, there is considerable variation. For example, Dewey's (1938a) pragmatism refers to science as an approach to reasoning; Toulmin's (1972) pragmatic point of view provides historical evidence from the history of science to examine conceptual change over time; Rorty's (1991) pragmatism seeks to change the nature of the conversation from technical philosophical debate to thinking about the usefulness of knowledge, be it science or other. Thus, the nature of philosophy of science is itself variable and like science fields experiences changes through research.

Third, philosophy of science has historically been normative and relatively apolitical (with a few exceptions, see Matthews 2009; Rouse 1996). Some of the central goals of philosophy of science concern questions about how science should be practiced, rather than the actual practices occurring in real settings. While some motivation for the study of scientific reasoning emerged from the realization of scientific knowledge as remarkably (and perhaps uniquely) reliable, the focus of philosophy of science has historically been on studying structure and change of scientific theories (Suppe 1977). Machamer (1998) characterized philosophy of science as concerned with the nature and character of scientific theories, the history and nature of inquiry, the value systems of scientists, and the effects and influences of science in society. While such a view expands beyond a focus on theory, the focus of the discipline has traditionally been normative – thinking about ways that reasoning should occur to lead to reliable results. This poses challenges to educators. Developing an inquiry orientation around socioscientific issues requires some consideration of the messy, ill-formed reasoning and ambiguity that surrounds science in society. Additionally, even in highly controlled settings, the reasoning patterns of students are likely to vary from the logical rigor demonstrated in philosophy. Therefore, models of conceptual change from science disciplines can at best be viewed as analogies for promoting thinking about student learning.

Fourth, the complexity of philosophy of science, and science studies more generally, particularly the empirical study of scientific practices (such as that found in the sociology and anthropology of science), poses challenges about how to characterize the nature of scientific knowledge and practices for students (Kelly et al. 1993). The rich debates within philosophy of science require specialized knowledge and an understanding of the history of ideas in this domain. Furthermore, the nature of science within philosophy changes. The complexities of science suggest that there is no one nature of science, but rather natures of the sciences (Kelly 2008), and that learning about the knowledge and practices of scientific disciplines requires engaging with such practices in particular domains (Rudolph 2000; Schwab 1960). Philosophy of science offers insight into knowledge in the various disciplines, but is not readily applicable to inquiry science teaching.

42.4 Philosophy of Science and Inquiry

I have argued that teaching science as inquiry poses a number of serious challenges. I have subsequently argued that drawing implications from the philosophy of science similarly for inquiry is problematic. But surely a field dedicated to understanding the bases of scientific knowledge should have something important to say to those seeking to teach science. Issues such as observation, experimentation, inference, and explanation seem relevant to learning about the workings of science. Yet, such practices pose challenges for novice learners who may not have the conceptual and epistemic bases to engage in such scientific practices in inquiry settings.

What can the philosophy of science offer? I argue that despite potential problems of implementation, philosophy of science contributes much, including methods for posing questions about science, models for serious thinking about science, understandings about aspects of scientific inquiry, and a skeptical orientation regarding ways that science is characterized in curriculum materials and instruction.

42.4.1 An Inquiry Stance Toward the Nature of Inquiry

Philosophy of science provides methods for posing questions about science, scientific activity, and values entailed in such inquiry. Philosophy of science steps back from the details of specific scientific investigations, debates, and controversies and seeks to examine the rational basis for theory choice. Over time, the characterization of theory change as depicted in philosophy of science has changed, and the debates continue. For example, certain versions of early understandings of logical empiricism sought to understand the logic of theory choice. This perspective attempted to view theories as predicting devices and focused on the cognitive content (often viewed as the empirical consequences) of particular theories. Alternatives of various sorts to this depiction emerged after Kuhn's (1962/1996) influential view of theories as connected to overarching paradigms that influence the nature of observation. Recognizing the importance of theories, beyond their empirical consequences, led to a number of developments in empiricism and scientific realism, along with various social constructionist views of science. Across the perspectives, philosophy of science continues to engage in inquiry into the inquiry processes of science.

Modeling inquiry into inquiry has two implications for science teaching and learning. First, question posing serves as a model for school science pedagogy and research into learning science as inquiry. For pedagogy, inquiry requires finding ways to pose questions and problems. Indeed, recognizing what is a good question to ask is often a key feature of inquiry. For research into inquiry, posing questions about the inquiry process and examining ways that inquiry changes over time can advance educational thinking about science education. Second, inquiry into inquiry in philosophy of science demonstrates the importance of thinking about epistemic practices within a community and the value of shared repertoires for investigations and argumentation.

42.4.2 Development of Understandings About Aspects of Scientific Inquiry

Philosophy of science may identify educational perspectives on science that are not readily available through causal observation, or even participation. Careful analysis of theory change, induction, and explanation in the field of philosophy of science can lead to understandings about the nature of science. Furthermore, increasingly philosophy of science is being influenced by the empirical study of scientific practice (Fuller 1988). These studies are informing philosophy of science in ways that bring further relevance to the consideration of inquiry approach in education. Four examples illustrate this case.

First, across perspectives in the philosophy of science, there is wide agreement about the theory dependence of scientific methods. Hypotheses are not tested one by one, but rather a set of auxiliary hypotheses are held constant for a given domain of knowledge for each investigation. Disagreements about results, say for a tested hypothesis, include evaluations of plausibility of the auxiliary hypotheses, as much as the meaning of empirical results for the tested hypothesis. Part of what is at stake in advancing knowledge is understanding how theory, methods, and specific results map onto the plausibility of background theoretical knowledge. Furthermore, such investigations are the product of persuasive arguments and knowledge emerging out of (often) strenuous debates. Thus, theory dependence advances in knowledge situated within a relevant epistemic community.

Second, scientists engage in social practices for years before learning to recognize phenomena from the point of view of the discipline (that is to "see as") (Goodwin 1994; Kuhn 1962//1996; Wittgenstein 1953/1958). Such socialization provides stability in the field and provides the basis for inquiry. Becoming a relevant observer or speaker or member generally requires a significant apprenticeship, as a new member of a community learns the practices and applied knowledge of the research area in question. This view builds on the work of Wittgenstein (1958) and has been shown from historical (Hanson 1958; Kuhn 1962/1996) and sociological (Collins 1985) perspectives. Importantly, engaging in social practices entails learning the discourse processes and nuanced meanings of a field. This has led to careful examination of the ways that discourse processes make visible events for observers (Lynch 1993).

Third, the use of models has become recognized as important for scientific inquiry (Giere 1999). Models in science are viewed as holding an internal structure that represent aspects of some phenomenon or mechanism (Machamer 1998). These models come in different sorts (e.g., analogous physical conditions, mathematical representations, idealized cognitive models) and serve different roles at various stages of knowledge construction (Schwarz et al. 2009). Modeling in science education draws from philosophy of science and cognitive theory. For example, Windschitl et al. (2008) proposed a view of science that focuses student discourse on learning scientific concepts. They identified several epistemic characteristics of scientific knowledge represented in models. Such models are "testable, revisable, explanatory, conjectural, and generative" (p. 943). Windschitl and colleagues propose a model-based inquiry approach that uses a set of conversations to organize knowledge, generate testable research questions, seek evidence, and construct an argument. This model-based approach to inquiry offers the possibility of moving students beyond learning only theoretical knowledge by situating them in a community that considers the epistemic criteria for scientific models (Pluta et al. 2011). Such a view is consistent with the dialogical perspectives in social epistemology.

Finally, the complexities and variety of activities that might count as science have made characterizing these activities as a whole increasingly problematic. While at one time physics may have served as a model of science, emerging views of science recognize important disciplinary differences. Furthermore, the disunity of science and the range of the many fields that can properly be called science require that understandings, such as the nature of science, and disciplinary inquiry, such as the philosophy of science, look at specific ways the actual work of science is accomplished. This issue has been brought to science education in reviews of the nature of science (Kelly et al. 1998) and in specific applications to disciplinary knowledge within fields of inquiry such as biology education (Rudolph and Stewart 1998), chemistry education (Erduran 2001), and geology education (Ault 1998).

42.4.3 Values of Scientific Communities

Philosophy of science identifies values undergirding scientific inquiry. Such values are relevant to inquiry in science education. As an illustrative example, I consider the identification of values in science and the importance of establishing discourse ethics for fair debate in science fields. Longino's (1990, 2002) social epistemology articulates ways that productive discourse can be accomplished in scientific communities. In her work Longino (1990) examined both constitutive values internal to scientific communities and contextual values that influence assumptions in science. Her work considered how values for discourse could be established to promote reason and objectivity given the deeply value-laden work of science. Her solution was to propose a set of four social norms for social knowledge (Longino 1990, 2002): The *venue* refers to the need for publicly recognized forums for the criticism of evidence, methods, assumptions, and reasoning. Everyday venues may include research meetings, conference presentations, and publications. *Uptake* refers to the extent to which a community tolerates dissent and subjects its beliefs and theories to modification over time in response to critical discourse. This value is somewhat contested, as in some areas dissent can be interpreted as not adhering to the best available explanation. *Publicly recognized standards* are needed as a basis for criticism of the prevailing theories, hypotheses, and observational practices. These standards contribute to framing debates regarding how criticism is made relevant to the goals of the inquiring community. One would expect public standards to evolve over time as research groups, communities, and disciplines develop new knowledge and practices. Finally, Longino (2002) argued for communities characterized by *equality of intellectual authority*. This equality needs to be tempered, so differing levels of expertise and knowledge are appropriately considered. While these are values identified as prescriptive for public discourse in science, such values may be applicable to inquiry in science education (Kelly 2008).

42.4.4 Developing Skepticism Toward Portrayals of Science in Curriculum Materials and Instruction

Philosophy of science can help educators promote a healthy skepticism regarding how science is characterized in curriculum materials and instruction. Inquiry in science education is often seen as a means to realizing understandings about the nature of science – importantly this often entails opportunities to raise issues about science (Crawford et al. 2000). Machamer (1998) characterizes the philosophy of science as "the discipline that studies the history and structure of inquiry" (p. 2). The study of inquiry, thus, should evince aspects of the ways that disciplinary knowledge is constructed, assessed, used, and communicated. These issues have been taken up in science education, relying on the philosophy of science and science studies more generally. A fundamental question is whether there can be a consensus view characterizing the nature of science as a set of declarative statements, or if inquiry can serve as a means for engaging in aspects of disciplinary practice where epistemological issues arise. For example, Rudolph (2000) cautions about assuming a generalized view of science or a standard set of assumptions about the nature of science, given the disciplinary differences and the heterogeneous practices across the workings of science in its many forms and disciplines. Irzik and Nola (2011) make similar arguments against a consensus view of the nature of science. Their perspective takes a family resemblance view to account for the many ways science differs across disciplinary perspectives. Importantly, these authors note that while actual inquiry practices vary, engaging in "data collecting, classifying, analyzing, experimenting, and making inferences" (p. 593) is central to developing understandings of science. Considerations of the criteria for which such practices are relevant to a given situation, and under what conditions, can lead to productive conversations about how to characterize science for the various educational purposes of different science education programs. For example, Van Dijk (2011) proposed that a family resemblance view of the nature of science offers the flexibility for the fields of science communication where promoting scientific literacy is a key goal. This perspective recognizes the disunity of science and argues against viewing science as a set of declarative statements, suggesting that such a perspective offers ways of communicating the nuances in the variation across images of science.

Allchin (2011) suggests that achieving a robust view of science requires abilities to make sense and assess the validity of scientific claims. As suggested in the preceding section on inquiry into inquiry, philosophy of science can model the reasoning needed to understand the complexities of science while supporting skepticism toward generalized statements about science. Allchin proposes methods for evaluating students' understanding through engaging students in case studies of assessment of scientific claims, thus showing how the substantive knowledge and explanatory ideals of a given discipline is related to the inquiry methods (Ault and Dodick 2010; Kelly et al. 2000). This view of inquiry entails engagement with knowledge of the natural, designed, or socioscientific worlds, for a given task, and thus takes the expanded view of inquiry (beyond just hands-on science) described in the introduction of this chapter.

42.5 Toward a Sociocultural Philosophy of Science for Education

42.5.1 Shift in Epistemic Subject from the Individual to a Collective

Philosophy of science has shifted the epistemic subject from the individual learner to the relevant social group (Fuller 1988; Longino 2002). Such a shift provides the basis for a thoroughly social view of knowledge and practice in science (Lynch 1993) and science education (Kelly and Chen 1999). There are clear curricular implications for a social epistemology. These include creating practical experiences that take into account the extant knowledge of the students, designing investigations that acknowledge the interpretative flexibility of empirical evidence, and situating decisions about experimental results and socioscientific issues in a dialogical process (Kelly 2008). The social basis of scientific knowledge has a long history. From Fleck's (1935/1979) thought collective, Wittgenstein's (1958) language games, Kuhn's (1962/1996) paradigms, to Toulmin's (1972) constellation of explanatory procedures, to Longino's (1990) shared values, a continuous thread runs through twentieth-century philosophy of science: the sociocultural basis for scientific progress.

There are many examples that illustrate the importance of the sociocultural basis of scientific progress. Three examples highlight some of the relationships with inquiry: the *sociohistorical contexts of scientific discovery*, the *acculturation of new members to a community*, and the *relevance of epistemic criteria and evaluation of knowledge claims*. Before reviewing their implications, it is important to recognize the distinction between the aims of scientific groups, which are orientated toward producing new knowledge, and the aims of education, which include acculturating novices into ways of understanding the natural world. Scientific and educational institutions have different purposes, and failing to recognize the differences confounds aspects of inquiry with discovery, learning, and so forth. Inquiry in science activity may lead to new knowledge. Inquiry in education serves to instruct members how to engage in relevant specific processes of investigation, use concepts in context, and develop means for understanding community practices. Under some circumstances, inquiry in educational settings generates new knowledge within the local community, thus showing some similarity with scientific communities.

Advances in science emerge from *sociohistorical contexts* where relevant groups of inquirers draw from extant knowledge, design and execute ways of collecting evidence, and propose solutions and evaluate solutions to outstanding, communally recognized problems. Fleck's (1935/1979) analysis of the science of syphilology provides a telling case. A variety of notions of the origins and causes of syphilis emerged from various social constituents. Religious, astrological, and medical communities proposed ways of understanding the origins and nature of the disease. The eventual development of the idea of syphilis as an infectious disease occurred through agonistic debates in which both the nature of the causal entity and the relevance of certain preconditions were simultaneously examined. For any experimental result to be taken as evidence, a whole set of preconditions and assumptions of the thought collective need to be taken into consideration. The eventual success of the identification of the infectious agent was the result of the collective effort of a community of health officials, whose contributions and work "cannot easily be dissected for individual attribution" (p. 41). The debate had to be won around the epistemic criteria for evidence – not just around the nature of the evidence from the different perspectives.

A second example of the epistemic shift relevant to inquiry for education is the manner that newcomers are acculturated into particular ways of seeing, communicating, and being. This realization about the substantive and important socialization into the ways of being in science counters forms of positivism (Ayer 1952) that based scientific progress on logic and objective experimental facts (although see Carnap 1950). These ways of being are dependent on the social practices of a relevant community (Mody and Kaiser 2008). Much of the work of apprenticeship for the ways of seeing, communicating, and being entails active participation in the practices of a relevant community. Learning to participate and become a member involves collective action. Understanding the ways that the language of a group operates, the nuances in meaning, and the path to modification in such meaning involves use of discourse in contexts. Furthermore, the completion of such an apprenticeship may be critical to being taken seriously by peers (Collins 1985).

A third example of social processes involved in scientific progress concerns the epistemic criteria for the evaluation of knowledge claims. Rather than viewing reasoning in science as a logical process of hypothesis testing, contemporary philosophy of science recognizes the dialectical processes of persuasion, debate, and critique. Indeed, scientific knowledge is social knowledge to the extent that knowledge claims are judged in relevant disciplinary communities. Longino (2002) and Habermas (1990) each have proposed norms for productive conversations in communities that respect alternatives but focus clearly on the strength of marshalling evidence. This leads to implications for inquiry centered on the social basis for decisions and the importance of using evidence in science. A dialectic approach to the construction of knowledge claims has plausible relevance to education. Nevertheless, such an approach needs to consider the local context and participants. Interesting questions about inquiry can be raised about students' developmental ages and abilities and variations regarding the science topic at hand.

42.5.2 Philosophy of Science and Learning

The relationship of philosophy of science and learning has been a central part of numerous developments in science education. One intersection occurred during a focus on constructivist learning in science education. Constructivism entered science education through a focus on students' ideas and understandings, building initially on Piaget (for review, see Kelly 1997). These learning theories and their close cousins, such as conceptual change theory, brought a welcomed focus on students' conceptions. Through careful attention to how students made sense of science phenomena, researchers were able to examine learning from the learners' point of view. This had a significant impact on science education and brought in philosophy of science. For example, the development of the alternative conceptions movement and conceptual change theory both used the work of Kuhn (1962/1996) and others to consider how students' constellation of conceptions served as framework for sensemaking. These foci led to pedagogy attending to students' sensemaking and provided opportunities for students to be actively involved in knowledge construction.

Despite the many positive contributions of constructivism to science education, there were two central philosophical problems. First, many forms of constructivism, particularly radical constructivism, set their epistemological commitments on the mind of the individual learner. This view conceptualized the problem of knowledge and learning as a cognizing subject making sense through exploration. This epistemological orientation ignored the important contributions from philosophy of language and other social views. Thus, by committing to a Cartesian subject, the constructivist orientation was ill equipped to integrate discourse and consider the value of social practice (Kelly 1997). Rather than viewing learning as socialization into a community, constructivists tended to view learning as changes in the cognitive structure of an individual mind. Second, some forms of constructivism confounded the construction of knowledge with ontological questions about reality and world making. Radical constructivism in particular was clear about its commitment to an idealist ontology and failed to understand the nuanced ways other ontological commitments could adhere to similarly reasonable pedagogies (see contributions in Matthews 1998).

A serious competitor to constructivist theories of learning emerged in the form of sociocultural theory. This view of learning conceptualizes the problem of learning as one of participation and appropriation of knowledge and practices of some relevant group. Central to this view is the important role of discourse processes through which everyday events are constructed (Kelly and Green 1998). By viewing learning as acculturation, the role of social processes and cultural practices are emphasized. From this point of view, as groups affiliate over time, they form particular ways of speaking, acting, and being that are defined by the group membership and evolve as the group changes (Gee and Green 1998; Kelly 2008; Kelly et al. 1998). Discourse practices established by the group become cultural tools for members to construct knowledge. These cultural tools, signs, and symbols mediate social interaction, which forms the basis for learning (Vygotsky 1978). Learning does not occur only for individuals because the cultural tools themselves serve as resources for members and evolve as members internalize the common practices and transform them through externalization (Engestrom 1999). Thus, this view of learning entails more than changes in the internalized cognitive structure of individual minds; instead, participants learn to be members of a group with common knowledge, identity, and affiliation through shared cultural practices that constitute membership in a community.

Sociocultural psychology and philosophy of science share some important central tenets and premises about science, knowledge, and inquiry. Both represent a shift in the epistemic subject from the individual learner or scientist to the relevant epistemic *community*, the relevance of agency within the potential created by a social language, and the value of dialectical processes for proposing, evaluating, and testing knowledge claims. Perspectives from Vygotsky (1978) and neo-Vygotskians (Cole and Engestrom 1993) evince the importance of considering how inter-psychological processes can be internalized by individual learners. Thus, much like the social epistemology in the philosophy of science (Fuller 1988; Longino 2002; Toulmin 1972), the individual has agency and plays a key role in the development of knowledge but does so within the social languages of a relevant community. This suggests that instructional design for inquiry should consider how social practices are established and used to communicate ways of inquiring into the natural world. Such communication occurs across events leading to the development of knowledge, including the problem-posing phase of inquiry, the sensemaking talk around investigations, deliberation around meaning of results, and evaluation of the epistemic criteria for assessing proposed ideas, models, and theories.

42.6 Conclusion: Philosophical Considerations for Inquiry Teaching and Learning

Science education has considered inquiry as a goal for reform a number of times across decades – for examples, see Dewey (1929), Schwab (1960), Rutherford (1964), and NRC (1996). Whether or not inquiry was in the foreground, we have seen proposed educational change in the form of goals, standards, and frameworks. Reforms come and go and sometimes come back (Cuban 1990), yet careful consideration of aims should always be present in the conversation about education. This chapter examined philosophical considerations of inquiry, yet science education reform in any form or name can be informed by philosophy of science. Reform in education should not be aimed to reach final resolution of the issues around curriculum, instruction, and assessment once and for all. Rather, reform is a process that can include participants as part of a vibrant democracy where agency and identity are formed through active engagement in educational decision-making (Strike 1998).

This chapter argued for a view of philosophy informed by the empirical study of everyday practice (Fuller 1988; Kelly and Chen 1999; Lynch 1993). I conclude by first considering ways that this view of philosophy can inform science education. I then offer some research directions for the field of history, philosophy, and sociology of science and science teaching.

Philosophy has the potential to inform educational practice and ways of thinking about reform in educational policy. First, philosophy offers ways of posing questions. Posing questions and examining implications represent a contribution of such philosophical considerations. A number of central questions continue to be posed: What counts as understanding? What does it mean to learn? What is knowledge?

How can disciplinary knowledge and practice be assessed? Posing questions and examining in detail any proposed reform offer a contribution to the overall debate in educational reform. Second, philosophy can contribute through conceptual sorting. Through philosophical analysis of the conceptual content of educational texts (policy, curriculum, frameworks, standards) and of education events (research, teaching), philosophy can bring clarity or identify areas of ambiguity. Developing understandings about the nature of knowing, inquiry, and meaning is central to reform that progresses and advances thinking about education. While such meanings can be informed by empirical study, understanding the meaning of inquiry requires careful thought and analysis. The study of everyday practice in science and education settings (Kelly et al. 2012; Lynch 1993) can inform our views about the nature of science, inquiry, and meaning; nevertheless, there is considerable theoretical work needed to render empirical results informative. Thus, normative decisions about directions for science education cannot be answered by empirical study alone, or even more empirical studies – a balance must be struck between careful, descriptive studies and philosophical considerations of meaning. Third, philosophy of science can inform our field by scrutinizing the nature of education research, including the important work of understanding ways to develop productive conversations across theoretical traditions (Kelly 2006). Science and education are human endeavors that require ideas to be generated and assessed through dialectic processes. The field of educational research should consider ways to enhance discourse around educational practice.

With these philosophical considerations in mind, I now consider some plausible research directions for science education regarding inquiry. Inquiry in science education has taken many forms and served different goals (Abd-El-Khalick et al. 2004). In this chapter I identified a number of problematic aspects to thinking about learning science as inquiry. By drawing from a social epistemology in the philosophy of science, I have examined reasons why inquiry as an instructional approach has both potential and drawbacks. The efficacy of this approach depends crucially on how it is implemented, for whom, under what conditions, and for what purposes. I propose four areas for research regarding inquiry in science education.

First, we learned much as a field from the detailed, analytical work of the anthropology and sociology of science (e.g., Knorr-Cetina 1999). The study of everyday practice makes clear the social processes by which *what counts* as science is discussed, debated, and determined. Inquiry contexts, such as the model-based inquiry approach of Windschitl and colleagues (2008), provide a context to examine empirically the value of such approaches for science education. While science studies have their drawbacks, they offer insights into the inner workings of the various sciences. The methodological orientation to examine inquiry as it is interactionally accomplished in everyday life suggests that a similar approach in science education can be fruitful. Close, careful studies of the discourse events around inquiry can illustrate how inquiry is enacted. Contexts such as design challenges, investigations, and studies of socioscientific issues provide potentially inventive pedagogies that can be investigated empirically.

Second, there is a persistent lack of interest among students in pursuing science (Sjøberg and Schreiner 2010). Inquiry models for science instruction have been proposed as a means to address such concerns, beginning with Schwab (1960) and continuing thereafter. Yet, it is not clear that engaging students in inquiry, either into the natural world through investigations or into the socioscientific world through debate, will necessarily increase student interest in science. Research derived from philosophy of science may make science more real, authentic, or consistent with professional practice, but this may not take into account students' views and interests. Furthermore, studies examining the referent for science beyond that of professional science may point to directions that are better at engaging students – for example, ways that citizens use science to address everyday environmental concerns. Such studies would pose a new set of questions about what counts as science for the field.

Third, striving to meet the conceptual, epistemic, and social goals of science education (Duschl 2008) requires a critical analysis and discussions about the nature of inquiry. Such research would need to be reflexive about inquiry into inquiry. Work in science studies and the philosophy of education may be helpful for understanding how inquiry can be conceptualized in science education. I have argued both for the descriptive, empirical studies of science and science education and for the importance of the normative or moral arguments for reason, science, and education. The field of science education can be informed by both perspectives.

Fourth, inquiry most broadly construed entails learning and self-actualization. The educational goal of inquiry should not only be to meet specific standards, concepts, or procedures, but rather to develop the capacity for further learning. Through engagement in the sociocultural resources of other people and through interaction with the natural, designed, or social world, learners can develop an enhanced capacity to learn and develop new ideas. Education from inquiry should develop the ability to engage in more inquiry.

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Chapter 43
Research on Student Learning in Science: A Wittgensteinian Perspective

Wendy Sherman Heckler

> *[W]e cannot avoid thinking about [Wittgenstein's] methods and their rationale if we are to find his philosophy intelligible.*
>
> (Minar 1995, p. 416)

43.1 Introduction

In the science education research literature, there is an overwhelming tendency among those who reference Wittgenstein's work to do so in ordinary ways. In other words, Wittgenstein is cited as if he has offered up a corrective theory that we can and should apply to our studies of the human condition; "meaning-in-context," "family resemblance," or "language games" come first to mind. But this chapter will suggest that such a tendency misses the central point of Wittgenstein's work: to model an alternative orientation for the philosophical project.

Wittgenstein warned against our becoming "bewitched" by natural language. He felt that many of the time-honored problems of philosophy were not problems at all, but only puzzles that result from a lack of clarity about how our language works. For example, we tend to see an expression such as "My back hurts!" solely as a report of a private experience. This is due to our picture of language as serving primarily or even exclusively to name things and, in particular, to name states of mind. Because of this representational notion of language, we tend to think of such expressions as reports of prior introspections or private experiences. As with "pain," so too with perceptions and thoughts: each person has access to an "inner world"

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of phenomena that no one else can breach. This raises difficult philosophical questions about how one's inner world coordinates with an outer world of external experiences; how we communicate with others, for instance, or how we "internalize" what we learn about the world. It underwrites venerable programs of skepticism, asking what we can know of other lives and worlds.

Wittgenstein thought that talk of private inner worlds was misguided and that philosophical misconceptions like this one arise from the grammar of our common expressions in tandem with this wrong-headed view of language. Pronouncements of being in pain are not reports of a check conducted over an internal state of affairs. Rather, Wittgenstein encourages us to think of such pronouncements as they are typically used: as a type of pain behavior, simply a way of acting when one is in pain. Describing one's pain is an alternative to crying out, not the result of an inward examination and processing of phenomena known only to oneself (cf., Hacker 1999).

Wittgenstein described the proper role of philosophy as akin to therapy. He thought the philosopher's task was to clear up conceptual confusions at play in our language or to "show the fly the way out of the bottle." Rather than affirming one side or another of well-known philosophical debates, Wittgenstein questioned the assumptions on which the debates took place and attempted to dissolve puzzles by revealing them as artifacts of unexamined grammars.

It is understandably tempting for science education researchers to dismiss Wittgenstein's advice. After all, research in science education isn't doing philosophy; rather, we attempt to solve actual, empirical problems by conducting studies about teaching and learning and developing theoretical explanations of the results. But what if the assumptions underlying our empirical work suffer from conceptual confusion? For instance, if private worlds are suspect, what can be said of studies of how learners construct personal meaning of scientific concepts? Or, to suggest a more appropriately Wittgensteinian manner of stating the issue: what if the question of "how learners construct personal meaning of scientific concepts" is examined not as an empirical question at all but for its merits as a sensible conceptual one? This chapter takes interest in questions such as these in an effort to encourage better understanding of Wittgenstein's unique contributions to philosophy and by extension, to the social sciences.

43.2 Wittgenstein's Life and Philosophical Contribution

Ludwig Wittgenstein's (1889–1951) life was extraordinary in its range of experiences; in contrast, his philosophical work remains notable for its single-minded focus on the implications of his alternative view of the project of philosophy (Monk 1990, 2011). Born in Vienna to an aristocratic family, Wittgenstein regularly interacted with musicians, artists, and intellectuals. While he is known for his career as a Professor of Philosophy at the University of Cambridge, Wittgenstein also sought fulfillment in various other vocations throughout his lifetime. He served in the

Austrian Army during World War I, including some time on the front lines in Russia and Italy and nearly a year spent as a prisoner of war. After the war, Wittgenstein took up elementary school teaching for a time in rural, largely impoverished Austrian villages in an attempt to restore his humanity and improve his soul. During World War II, and although it meant abandoning his professorship at Cambridge, he took a job at Guy's Hospital (in London) where he prepared pharmaceutical ointments and delivered medicine to patients. Wittgenstein was naturally inclined toward technical-mechanical expertise, having originally aimed to study aeronautical engineering as a young university student. While working for a time as an architect, he designed elements such as windows, doors, and radiators for his sister Gretl's home in Vienna. Wittgenstein's emotional life mirrored this vacillating search for vocational contentment: he was sensitive, temperamental, and by turns suicidal. He was also driven to perfection in each task and relationship he undertook and therefore routinely profoundly disappointed with the inability to achieve it (Monk 1990).

Wittgenstein's introduction to philosophical study resulted from his focus on mathematics. After beginning an education in engineering at the University of Manchester, he took interest in mathematics and its philosophical foundations. This interest led to a correspondence with Gottlob Frege, and most biographers credit Frege with encouraging Wittgenstein to work with Bertrand Russell at Cambridge (Monk 1990; Richter 2004; alternatively see Anscombe 1995). His studies eventually led to the ideas published in the *Tractatus Logico-Philosophicus,* a work Anscombe locates "halfway between Frege and Russell – at least in some ways" (1995, p. 396). In the *Tractatus* Wittgenstein is credited with advancing a "picture theory of meaning," in which the sense of a proposition is founded on its accurate portrayal of empirical matters (Richter 2004). According to common interpretation, Wittgenstein's *Tractatus* argues that logic can be shown through language but at the same time, logical propositions themselves are nonsensical (since logical propositions do not reflect actual worldly objects). The *Tractatus* was highly influential on members of the Vienna Circle, so that these logical empiricists were inspired to dismiss the philosophical ambition to find metaphysical truths and to equate philosophy with understanding "the logic of scientific language" (Hacker 2007a). Further, based on ideas from the *Tractatus* the Vienna Circle "proposed the principle of verification as the key to the notion of linguistic meaning and invoked verifiability as a criterion of meaningfulness" (Hacker 2007a, p. 2).

After the publication of the *Tractatus*, Wittgenstein gave up philosophy for a time but was eventually lured back to Cambridge and to revisiting his ideas based on conversations he had with members of the Vienna Circle and with Frank Ramsey (Monk 1990). As he lectured and worked with colleagues at Cambridge from the 1930s on, his thinking began to depart significantly from his earlier work.[1] In particular,

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[1] But see Crary and Read (2000) for an exploration of the continuity in Wittgenstein's early and later philosophy.

Wittgenstein developed a wide-ranging and forceful rebuttal of the representationalist view of language. His conception of the nature of philosophy itself also matured, leading him to argue that the discipline is not characterized by foundational problems that need universal solutions, but rather consists in various and persistent missteps in the use of language which muddle our perspective. Although he prepared numerous manuscript versions of these ideas and came close to publishing them on several occasions, he instead left instructions with a cadre of trusted students for posthumous publication of his later writings (Monk 1990). The *Philosophical Investigations* and other subsequent publications drawn from his *Nachlass* express Wittgenstein's later philosophy, which argued essentially that, properly conceived, philosophy was a methodology for clearing conceptual confusions rather than a search for theoretical or generalized truths. Through philosophical analysis, we seek to understand how language contributes to – in fact, engenders – supposed philosophical puzzles such as the "mysteries" of consciousness, or introspective, private access to inner states of being. Philosophy's task was ideally to dissolve puzzles and not to write alternate theories that might account for them (Monk 2011).

Wittgenstein's later works[2] are often cited for their insights into a wide variety of philosophical topics, including meaning and understanding, rule following, the "inner" and "outer" realms of human activity, and the grounds of "certainty" (see Kenny 2006). In contrast to the representationalist view of language expressed in his earlier work, these writings identify the meaning of an expression as its rule-governed use in language, inextricably tied to its use in our lives (Diamond 1989). As Hacker summarizes,

> The meaning of an expression, with marginal qualifications, is its use. It is also what is understood by anyone who understands or knows what an expression means. And it is what is given by an explanation of meaning. An explanation of meaning, even a humdrum explanation given by means of a series of examples, is a rule – a standard of correctness – for the use of the explanandum. (2007b, p. 4)

Language does work other than representing; most simply, language expresses (Hacker 1999). This focus on the nature of language becomes the basis for Wittgenstein's therapeutic philosophical method: under careful scrutiny of their roles in language, ordinary concepts "dressed up" as theoretical ones lose their beguiling nature.

This chapter will focus primarily on Wittgenstein's later writings, for how they have obtained relevance in the science education research literature, and in particular as related to students' learning of science. Central to the treatment – and the idea will be revisited – is Wittgenstein's aversion to the "craving for generality" that marks normative academic discourses. The concepts emanating from his philosophy should not be read as pronouncements or contributions to a general theory. Rather, Wittgenstein's writings serve as exemplars in their own contexts and as lessons on how to "do philosophy" as a conceptual interrogation on any next relevant occasion (Hacker 1999, 2007b; Monk 1990).

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[2] See, e.g., Wittgenstein (1958, 1960, 1967, 1969, 1980).

43.3 The Place of Wittgenstein's Writings in Science Education

Wittgenstein remains a relatively marginal figure in science education research. However, his work has been invoked with increasing regularity, especially since what might be termed the "social turn" in research on learning in (science) education (see Gergen 1985 for a formulation of this movement in psychology more generally). As Vygotsky's theories of learning became more prominent in educational studies, researchers sought to understand the social aspects of human development, especially through discursive interaction. Wittgenstein's writings on "private language" and the character of language more generally are a natural resource for consultation in this line of inquiry. Another source of Wittgenstein's influence has been through the social studies of science movement. Wittgenstein's corpus has been a central resource to sociological studies of science for the last two decades.[3] In turn, these studies have influenced science educators and the study of classroom science.

43.3.1 Wittgenstein as a Corrective to Conceptual Change Theory's Appeal to Rationality

Early mention of Wittgenstein in science education was in the context of the debate over the newly posited theory of conceptual change. "Conceptual change" theory was introduced as a disciplinary-specific alternative to Piaget's developmental theory of learning, where accommodation (or how perturbations could leverage significant revision of learners' conceptual knowledge schema) was hypothesized to mirror the process of theory change in professional science (Posner et al. 1982). According to Posner and colleagues' foundational formulation, scientific conceptions can only be integrated by a learner when there is dissatisfaction with existing (prescientific) conceptions and when the scientific concept in question is intelligible, plausible, and carries the potential for further productive use.

Critics of the conceptual change theory of learning invoked Wittgenstein in different ways in order to question Posner, Strike, Hewson, and Gertzog's characterization of learning as "a rational activity" that involves "a kind of inquiry" resulting in a learner "accept[ing] ideas because they are seen as intelligible and rational" (1982, p. 212). West and Pines (1983) argued for considering nonrational elements of students' ideas and learning and specifically suggested that learning involves "feelings of power, simplicity in complexity, aesthetics, and personal integrity" (p. 38). They cited the collection of Wittgenstein's writings published as *On Certainty* in their claim that even such rational-sounding notions as "doubt" and "certainty" are imbued with both rational and nonrational elements.

Garrison and Bentley (1990) provided a similar critique of the place of rationality in conceptual change, noting that Wittgenstein's discussion of language learning

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[3] See (Bloor 1983, 1992; Lynch 1992a, b, 1993).

allows for the existence of "preconceptual" learning. Preconceptual learning includes children's use of primitive forms of language (taught by imitation and training) when learning to talk. They argued that, in contrast, *rational* learning should be considered "learning-by-explanation" and that it would come later, with conceptual understanding. The distinction is important, according to Garrison and Bentley, because they contend that leaning science is similar to a child's first learning a language. In their view, the concepts of science are so unlike the concepts of everyday life that the "language games" taking place in each context are vastly different, even incommensurable. For this reason, Garrison and Bentley speculated that learning science may consist of initial-language-type, preconceptual learning relying on processes *other than* rational choice between competing conceptions. Prior to conceptual learning, individuals learn to participate in language games via imitation and drill, and they acquire a "world picture" (or rule-like system of enabling beliefs) through exemplars and persuasion.[4]

Cobern (1995) adopted Garrison and Bentley's starting point that science and everyday life are premised on very different world pictures, or as Cobern saw it, different cultural worldviews. According to Cobern, "science…is fundamentally an issue of culture" that "requires learning to see the world in a new and very different way" (1995, p. 292). Along with Garrison and Bentley, Cobern accepted Wittgenstein's assessment that "the acquisition of a fundamental viewpoint is an issue of persuasion and internalization, rather than instruction and learning" and that this was "due to the lack of sufficient common ground" (Cobern 1995, p. 293).

As a sociocultural perspective on learning gained prominence in science education, more researchers began turning from a view of rationality as the evidence of a universal logic of science to a view of rationality as an expression of various local, collective rationalities – including those of groups of scientists and ultimately individual classrooms. The Wittgensteinian-instructed philosopher Stephen Toulmin was quite influential in this development, a point that was outlined clearly in the work of Kelly and his colleagues:

> Analysis of Toulmin also showed that his view of conceptual change is based on a theory of rationality of science in which science is viewed, not as a universal set of inference rules or commitments to central theories, but as a collective set of commonly held concepts, practices, and actions of members of a group called "scientists." Thus, conceptual change can be viewed as a theory of rationality in that it makes visible what counts as reasons for changes in knowledge within a group. (Kelly and Green 1998, pp. 148–149)

Furthermore, by the late 1990s, the focus on rationality in conceptual change underscored some trends seen in the science education research literature on student learning more generally:

> Rationality does not mean that scientists nor students follow stepwise inferences from data to ontological truths. History, philosophy, and sociology of science all suggest that scientific theory choice is problematic, contextual, ill-structured (Barnes and Edge 1982; Collins and Pinch 1993; Kuhn 1970). We should not assume that the actions of individual

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[4] See Wagner (1983, pp. 610–611) for an earlier but similar argument based on Kuhn's philosophy.

> scientists are necessarily rational. Likewise, the possibility that rationality is local is accorded; that is, choices governing what counts as rational action are subject to the conventionalized practices of particular social groups (Rorty 1989; Strike 1984; Wittgenstein 1958). Nevertheless, incorporating rationality into educational theory allows for a way of talking about learning that appeals to the social nature of knowledge and the normative ideals for theory choice. (Kelly 1997, p. 365)

As will be discussed below, the impact of the field of science studies on views of students' science learning came into play more extensively during this time. In addition, science educators shifted from being concerned about learners as individual rational actors to focusing on rationality as a social practice and therefore on social aspects of learning science.

43.3.2 Wittgenstein's Philosophy as Supporting Views of Learning as a Sociolinguistic Process

In science education, Wittgenstein's work is often used to lend support to the notion that "learning is social" or some similar formulation that draws a contrast between the picture of learning as an individual comprehending and "internalizing" knowledge of the world and a picture of learning as something more like "the ability to participate in group life in a meaningful way." Wittgenstein's writings about the nature of language have been particularly influential in this regard, since talk can be indicative of either successful or marginal participation in group life. Notably too, Wittgenstein argued against the possibility of a private language known only to an introspecting subject (see, e.g., Hacker 1999). Initial interest in Wittgenstein's notion of "language games" was a precursor to these developments.

Using Wittgenstein's corpus, Stenhouse (1986) also critiqued the conceptual change literature in science education. He was concerned first with the nature of concepts, and second, with the nature of conceptual change. Citing Wittgenstein, Stenhouse introduced science educators to the idea that the acquisition of concepts is not to be thought of as the establishment of mental representations in the minds of individual learners. Rather, concept mastery is performative and linguistic: to understand a concept is to be able to use it correctly in context. In other words, "using a concept correctly" implies that one is able to follow the rules for the language game in play, e.g., science. For instance, a student who spoke earnestly of "the force on an object resulting from its acceleration" rather than the other way around would be judged to not yet understand the concept of "force." Stenhouse argued that this sense of concept attainment should already be familiar to teachers, who use schoolwork and test performance to assess students' conceptual understanding; teachers don't look at brains to assess understanding. He noted, "insofar as they are inter-personal and 'public,' all educational transactions must take place though language-games" (p. 417).

The language games Stenhouse (1986) envisioned for science and everyday life were varied and yet continuous with one another. He argued that what counts as using a concept correctly can be different in different language games, so that, for example, a child would not talk about “water” in the same way as a chemist would. In fact, Stenhouse suggested that language games were developmental, in the sense that the “language-games of ‘ordinary life’ are needed not only for initiating students into specialist language-games, but also in the setting up of these language games de novo by those who invented them” (p. 417). His recommendation for teachers was to take great care in understanding a child’s language game, so as to initiate conceptual change from within it.[5]

The notion of conceptual attainment as successful participation in language games has developed in the research literature since Stenhouse’s initial arguments. Kelly and Chen (1999) studied high school science classroom work from the perspective that “the meaning of a word, symbol, or construct is situationally defined by its use in a particular discourse practice (language game)” (p. 909). For high school students learning to construct evidence-based arguments in science, Kelly and Chen argued “that practice using terms in multiple contexts is central to understanding” (1999, p. 909). Relatedly, in advocating that classroom discourse structures change from the familiar initiation-response-evaluation (or I-R-E; see Mehan 1979) format to one of “transformative communication,” Polman and Pea (2001) characterized both types of discourse as Wittgensteinian language games. In the first case, students and teachers orient to IRE structures as the familiar – and allegedly problematic – language game of modern institutionalized schooling. On the other hand, using the transformative communication practices espoused by the authors is said to allow teachers’ work to instead focus on “transforming students’ actions into more successful ‘moves’ in the ‘language game’ of science” (Polman and Pea 2001, p. 227). Thus, some language games are scientific, and some not, and in this way the formulation of “language games” preserves our normative dispositions.

Although their focus was on the “complex of representations, tools, and activities of a discipline” that they label “disciplinary discourse,” Airey and Linder (2009) used the concept of language game to develop their treatment of how students learn (or attain fluency in) this disciplinary discourse. They argued that a “mutually accepted system” like a language game “can only occur if both student and lecturer have experienced the ways of knowing of some part of the discipline” and that “such ways of knowing may perhaps only be holistically experienced through certain types of disciplinary discourse” (p. 40). They differentiated between students’ imitation of discourse and their holistic understanding of it, saying that successful teachers notice when students are not playing a language game correctly and seek to remedy this in order for students to achieve fluent disciplinary understanding. Thus, the game formulation is tied to levels or stages of learning.

Gyllenpalm and Wickman (2011) employed a sociocultural perspective of analysis to study what they name the “inquiry emphasis conflation” in science education: Teachers in classrooms tend to mistakenly equate “experiment” with any pedagogical

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[5] In contrast, as noted earlier, Garrison and Bentley (1990) used Wittgenstein’s notion of language games to argue that learning science was a fundamentally different process than learning in everyday life. They promoted the necessity of a “break” with everyday experience for learning science.

"laboratory task" and "hypothesis" with "prediction about the outcome of a laboratory task." From their analytic perspective, a focus on language games highlights the ways in which individual actions are tied to cultural institutions; by looking at "pivot terms" that tie to "central aspect[s] of two or more cultural institutions and their associated activities" (p. 910), they can better understand the ways in which different meanings may impact educational goals.

While for some researchers the notion of "language game" in science education is used largely to underscore the idea of conceptual understanding as linguistic performance, for others, this participation in language necessarily shifts our focus on learning itself from an "individual process" to a "social" one. In characterizing the philosophical commitments of conceptual change theory in science education, Kelly (1997) argued that "learning science is an acculturation, an initiation into a set of language games" (p. 367). Through Toulmin's philosophy, Kelly also emphasized the public nature of language games and (per Wittgenstein) rejected the notion of individualized, "private" language games. He contrasted the radical constructivist attempt to map "social" processes onto presumed private language games with conceptual change theory's commitment to public, shared concepts "because of the socialization that learners experience in the process of learning science" (1997, p. 369). At the same time, students "may need to *internalize* these [acculturated, scientific] conceptions and language games" (p. 370, emphasis added), a notion which he differentiates from the radical constructivist claim that students must originally create or construct this knowledge on their own.[6]

Kelly and Crawford (1997) directly addressed the "socio-cognitive discontinuity" in educational theories about cognition and indeed argued for "resisting any association of cognition as separate from social" (p. 555). Ivarsson et al. (2002) continued in this direction. They integrated some of Wittgenstein's views with Vygotsky's learning theories in order to illustrate how some conceptual change research may be advancing misguided conclusions, due to a focus on individual cognition. In particular, Ivarsson and colleagues looked at students' understanding of the earth's shape and gravity when they were given maps to use as part of an interview protocol. They argued for rejecting the notion that inner processes underlie external (discursive and nondiscursive) action:

> There is no sense, following [Vygotskian and Wittgensteinian] perspectives, in assuming that there is a level of thinking that is "pure" and that underlies reasoning in human practices. We cannot separate thought processes, say in the context of doing geometry or playing chess, from the conceptual tools that are applicable to such activities. Thinking is the use of tools. Or, as Wittgenstein so suggestively put it in the context of the use of language: "When I think in language, there aren't 'meanings' going through my mind in addition to the verbal expressions: the language is itself the vehicle of thought" (Wittgenstein 1953, §329). (Ivarsson et al. 2002, p. 78)

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[6] However, even before Kelly's attempts at sorting out philosophical differences between these views, some radical constructivists hinted at a willingness to concede the sociality of language; Wheatley approvingly cited Bloor's pronouncement in his "commentary on Wittgenstein, 'The real source of 'life' in a word is provided not by the individual but by the society'" (Wheatley 1991, p. 11).

Students who were shown maps in Ivarsson, Schoultz, and Säljö's study had no difficulty identifying the shape of the earth as round, even though previous research indicated that a significant number of students have difficulty thinking of the earth in this way. In drawing attention to the interactional nature of their interviews, these researchers maintained that an attempt to study "mental processes" apart from cultural tools used in discourse is worthless: "There is nothing to be gained by positing such a level of inquiry as the one implied by a notion of pure cognition underpinning our thinking" (Ivarsson et al. 2002, p. 97).

In sum, as views about the social nature of cognitive processes became more commonplace in science education research, references to Wittgenstein were used to support those general arguments. The study of social aspects of learning science necessitated examination of real-world interactions between students and teachers. For many researchers, participation in "language games" became a way to conceive of learning that provided a welcome alternative to a view of learning science as acquiring suitable mental representations of scientific concepts. "Language games" have thus been used to reference the discourse structure in classrooms as well as to emphasize the location of conceptual understanding. Many studies of science learning that focus on classroom discourse theorize that learning involves a combination of social and individual elements; e.g., meaning is constructed through discourse and interaction but must be internalized by the individual. However, a few researchers have used Wittgenstein to support an argument for abandoning the individual-social dichotomy altogether.

43.3.3 Wittgenstein's Alignment with Science Studies and Its Influence in Science Education

In the late twentieth century, sociology of science gained prominence with science educators as a model of how to conceptualize and study science and thus study science learning in the classroom. This seemed a natural extension of the project that began with the conceptual change theory of learning; after all, students' attempts at scientific meaning making were seen to parallel those of scientists. Furthermore, as noted above, changing views about rationality – from one, universally correct version to many local kinds – were seen to necessitate close examination of knowledge production and use in an assortment of contexts, including science classrooms (cf., Kelly 1997).

Two sociologists studying scientific practice and noted in the science education literature are especially relevant in assessing Wittgenstein's influence on this research genre. Perhaps the most obvious connection between science studies and Wittgenstein occurs through the writings of David Bloor on the Strong Programme in the Sociology of Scientific Knowledge (SSK). Bloor relied on Wittgenstein to justify his SSK project because Wittgenstein's later writings discuss and acknowledge the rule-governed nature of human forms of life (specifically, of language use and mathematics). Bloor (1983) interpreted Wittgenstein as positing that social consensus determines the correct interpretation of a rule; if this is so, then sociology would naturally be in a position to explain the genesis of this consensus and thus to explain human knowledge (including knowledge of logic, mathematics, and science). Another frequently cited, Wittgensteinian-inspired sociologist who studied scientists at work is Michael Lynch. Interestingly, Lynch critiqued Bloor's interpretation of Wittgenstein's writings on rule following and their implications for science study. Lynch argued for understanding Wittgenstein not as having "made science and mathematics safe for sociology" but instead as having "made things entirely unsafe for the analytic social sciences" (1992a, p. 232). According to Lynch, Wittgenstein does not license sociology to be the final arbiter of explanations of knowledge construction. On this account, Wittgenstein's relevance for science education may be not only about our conceptualizations but our conceptualizations of social scientific analysis.

With his colleagues, Kelly integrated Wittgenstein's perspectives into sociocultural views of learning in studies conducted over the late 1990s and early 2000s. In addition to arguing for a social conception of learning, many of these studies drew a direct parallel between studies of classroom science learning and studies of science as conducted in professional laboratory settings. Kelly and Crawford (1997) described an approach to studying science classrooms that emulated the success of sociological studies of professional science:

> A common thread among at least two of these research traditions, the empirical program of relativism (Collins, 1981), and the Strong program (Bloor, 1976), is that they are empirical; that is, they explore the scientific enterprise as it unfolds through investigations of the actors and actions (for review, see Kelly, Carlsen, & Cunningham, 1993). We take a similar research methodological stance in this study: We explore school science through an ethnographic approach, studying the actions and actors that comprise the culture of a conceptual physics classroom. Through detailed, over-time analysis of the social and discursive practices of the members of one high school physics class, we seek to document the actual practice of school science as it is constructed, signaled, and acknowledged. (Kelly and Crawford 1997, p. 534)

Kelly and Crawford cited the Garfinkel et al. (1981) study of Cocke and Disney's discovery of the optical pulsar as exemplary of an approach for describing how a cultural object of science took shape from a series of inscriptions, over the course of data runs. Their own study of data runs in a conceptual physics classroom described students' ways of determining "what counted as the acceleration of carts rolling down an inclined ramp" (p. 545). Kelly, Brown and Crawford (2000) used a study of university chemistry laboratory work by Lynch et al. (1983) for inspiration in analyzing the ways in which "science" was "situationally defined" in a third grade classroom during an experiment on algae growth. In both the university chemistry lab and the elementary school algae experiment, "Written instructions and the suggested experimental design underspecified the actions required to make sense of and accomplish the task of a science experiment," so that "something more" was needed to complete the practical inquiry (p. 650). Kelly, Chen and Prothero (2000) noted that their perspective was informed by ethnomethodology (Lynch's analytic orientation) and that their empirical study of writing in a university oceanography course "provide[d] a specification of the epistemic activities" (p. 702) at play in the setting, a reference to Lynch's (1992a) discussion of the ways in which ethnomethodological studies of work provide an empirical extension of Wittgenstein's philosophy. Lynch (1992a) himself argued that this extension is "not a move into empirical sociology so much as an attempt to rediscover the sense of epistemology's central concepts and themes" (pp. 257–258) through their description as practical activities.

Lynch's (1992a) discussion of ethnomethodology as an extension of Wittgenstein's work was developed into his conception of "epistopics" (Lynch 1993). His intent in suggesting investigations of "observation, description, replication, testing, measurements, explanation, proof, and so on" was to "divorce [these terms] from a 'metatheoretical' aura and to attend to the manifest fact that they are *words*" (1993, p. 280, emphasis in original). In science education, Tapper (1999) used Lynch's epistopics as an organizing theme in his analysis of students' talk during laboratory practical work. Tapper noted that Wittgenstein's notions of language game and family resemblance are foundational to the concept of "epistopics," which Lynch talks about as practices that look different across different settings but share a family resemblance across a set of similar language games (Tapper 1999, p. 449).

Studies in the sociology of science used Wittgenstein's writings to authorize their project of careful examination of scientific practice, albeit in different ways. Science studies have served as exemplars and sources of analytic insight for researchers studying the "social construction of science" in classrooms. Although science educators have acknowledged the link between science studies and Wittgenstein's philosophy, it is not clear that the differences in interpretations of Wittgenstein's program by sociologists of science have been fully appreciated.[7]

43.3.4 Wittgenstein's Philosophy as the Basis for Analytic Approaches to the Study of Learning

A final theme to be examined is the use of Wittgenstein's writing in developing specific analytic programs or tools in science education. Aside from offering concepts that change our theoretical views of what is happening during science learning, Wittgenstein's philosophy has been taken as offering up imperatives for how to study the world around us. For example, Kelly (2005) focused on Wittgenstein's advice to "don't think, look!" as confirming the importance of empirical study of "*what* people come to know" and "*how* people come to know in various settings" (p. 86, emphasis added). Through empirical exemplars, he argued that descriptive studies of learning in science classrooms serve three purposes: to "illustrate how situated practices define meanings" (p. 88), to "make visible the practices involved in constructing and learning scientific knowledge" (p. 91) in order for science educators to direct interest in them, and to "focus on the everyday social practices of actual people" (p. 93), perhaps ultimately in order to "develo[p]

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[7] Papayannakos (2008) is an exception.

ways of understanding and empathizing, and thus improving human conditions" (p. 99). Notably, however, Kelly's (2005) focus on "don't think, look!" presented description as an alternative to nonempirical studies but did not specifically point to the divergence of a program of analytic *description* from the "craving for generality" (often via theoretical *explanations*) that typically marks all scholarly investigation, whether empirical or not (see *Zettel*, §314, and Wittgenstein 1960, p. 17).

On the other hand, Macbeth's (2000) study of an interview between a student and conceptual change researcher (a scene from the professional development materials developed as part of the Harvard-Smithsonian Private Universe Project) is descriptive and, although not explicitly Wittgensteinian, shows an attempt to "bring into view, and even clarify, the conceptualizations of a research literature" (p. 236). The study described a scene in which a researcher constructed a "completely dark room" in order to challenge a student's conception that she will be able (eventually) to see there. Macbeth invoked Wittgenstein throughout the study, not to identify particular constructs as objects of analysis, but rather to compare the scene at hand with various exemplars given by Wittgenstein in his later writings.[8] Notably, and in a manner quite different from most studies of students' conceptions, the diagnostic interview examined in the study is not described as being about the meanings of terms, e.g., "light" and "dark" and "vision." Rather, the interview discourse is considered for what work it is doing: the work of a diagnostic interview and simultaneously the work of producing a professional development exhibit for teachers. Descriptions are given of how questions are asked and heard differently by the student subject and teacher audience, but the analysis is not used to promote a new theoretical understanding of meaning or discourse. In taking science education research itself as the topic of interest, and showing how researchers attach "beliefs" and "understandings" to students through diagnostic interviews, Macbeth attempted to provide clarity about our professional analytic concepts.

The most sustained use of Wittgenstein's work as basis for an analytic program in science education originated with Wickman and Östman (e.g., 2002a, b), who introduced Wittgenstein's writings to science educators as the foundation for a "tools taken from Wittgenstein to analyze discourse change" (2002b, p. 603). Their acknowledged frustration was with a sociocultural view of learning, which addressed the connection between people's actions and the sociohistorical contexts of which they are a part, but did not specifically posit a process for changes in learning to occur. Since they accepted that meaning is given through discourse processes, Wickman and Östman proposed looking closely at discourse in order to pinpoint the circumstances of discourse change. They examined transcripts of (classroom-based) interaction in order to determine how meanings change for students in the course of a classroom activity.

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[8] For example, Macbeth describes how the student hears her interviewer's question "Have you ever been in a completely dark room?" as a reasonable query rather than as a professional science educator's attempt to ascertain whether she harbors a misconception about light and vision. He references Wittgenstein's comment "on how asking an Englishman if he has ever been to Budapest is quite different than asking if he has ever been to the moon" and notes that the student "hears the question about a "completely dark room" as of the former kind" (p. 242).

The methodology developed by Wickman and Östman involves analyzing student talk in order to determine which meanings appear to be "standing fast" for students and conversely where students apparently perceive gaps in understanding. They suggested that these gaps are filled when "participants establish new relations in terms of similarities and differences to what is standing fast" (2002b, p. 605). Finally, the analysis considers and sorts the gaps which are filled from those which continue to linger after the educational encounter. The authors cite their significant debt to Wittgenstein as follows:

> Wittgenstein explored the idea that it is relations that make the immediate intelligible. He noticed that "What stands fast does so, not because it is intrinsically obvious or convincing; it is rather held fast by what lies around it" (Wittgenstein 1969, p. 144). He elaborates this idea by referring to "family resemblances" when explaining the meaning of language-games (Wittgenstein 1953/1967, pp. 66–67): There is no single similarity that is common to all "games." Instead there is "a complicated network of similarities overlapping and criss-crossing: sometimes overall similarities, sometimes similarities of detail." These similarities connect everything we call games in the same way as "the various resemblances between members of a family." However, relations are not just similarities. Wittgenstein also refers to differences in his description of language-games.
>
> Hence, both similarities and differences beget "what is standing fast." However, Wittgenstein shows that an exhaustive description of all these relations for all possible contexts is not possible. Neither is there a single definition that is meaningful in all contexts. An explanation can only make sense if it relates to similarities and differences to what is already standing fast in a specific context. Meaning is tied to the context of a language-game. *Knowledge* could thus be understood as *relations of similarities and differences in what is immediately intelligible* and *learning* as *constructing new relations to what is immediately intelligible*. (Wickman and Östman 2002b, p. 605, emphasis added)

In other words, "language game" was conceived as a theoretical object employing the Wittgensteinian constructs of "standing fast" and "family resemblance" in order to provide alternative formulations of knowing and learning in science. But importantly, these constructs were used to determine the procedure for analysis of transcribed discourse occurring during science learning scenarios. Lines of transcript were scrutinized for terms that appeared to be understood by students (i.e., those that stand fast) and terms that appeared to need clarification (i.e., demonstrating a gap in understanding). Documentation of the ways in which students closed the gaps (by constructing relations to what is known) provided the authors with ways to describe science learning that could focus on issues related to specific science content lessons (e.g., chemical reactions or biological structures) or that could be used to answer larger questions about science education (e.g., the nature of student-teacher interaction or in situ misconceptions).

Originally, this method was used to study the ways in which students produce generalizations during laboratory work (Wickman and Östman 2002a) and to determine what students were able to learn about insect morphology in a university-level lab practical (Wickman and Östman 2002b). Over the next decade, other studies borrowed and refined the methodological approach. Wickman (2004) reframed the methodology as "practical epistemology analysis" and with it studied university students' learning during a chemistry laboratory activity in which unknowns were to be identified through (qualitative) analysis of reaction properties. Lidar et al. (2006) employed practical epistemology analysis to study the ways in which teachers' actions and students' apparent views of school science knowledge interacted in a seventh grade class engaged in chemistry activities.

Jakobson and Wickman (2007) studied children's spontaneous use of metaphors in learning science and determined that metaphors were used to construe relations between familiar and unfamiliar terms, to make aesthetic descriptions and evaluate classroom norms. In a related study, Jakobson and Wickman (2008) used practical epistemology analysis to further develop the connection between aesthetic judgment and normative participation in elementary school science. Hamza and Wickman (2008) asked whether the assumption in science education that misconceptions impact learning is true during real-time practical lab work and found through practical epistemology analysis that "misconceptions in electrochemistry did not constrain the ways students established relations to fill gaps noticed during the practical" (p. 160). Finally, Lidar et al. (2010) also used practical epistemology analysis to revisit the misconceptions literature in science education. Specifically they sought to illuminate a way in which individual experiences in learning might be synthesized with social and institutional ones, especially though examining the role of context and the use of artifacts in learning processes (see p. 693). Lidar and colleagues (2010) focused on children's conceptions of the earth and gravity and identified points at which different student groups 'take the learning path in different directions' perhaps "due to previous experiences or interaction with the teacher, peers, books, artifacts, or nature" (p. 706).

Combining practical epistemology analysis with analysis of teachers' epistemological moves (cf., Lidar et al. 2006) and with the analysis of companion meanings (or what might be otherwise known as the "hidden curriculum"), Lundqvist et al. (2009) developed an analytic program they labeled "communication analyses of companion meanings, or CACM" (p. 860). Again, Wittgenstein was cited for the insight that "people act without hesitation or doubt" such that most meanings can be seen to "stand fast" in talk (p. 863). As assumed in other practical epistemology analysis studies, Lundqvist and colleagues argued that "To learn something new, people have to create *relations* between the new and what already stands fast for them" (p. 864, emphasis in original). However, for students, teachers have a role in the learning process, and Lundqvist, Almqvist, and Östman noted that teachers' turns in discourse may serve to direct students and result in "changes in the students' practical epistemologies" in what can be seen as "confirming, instructional, reorienting, reconstructing, and generating moves" (p. 864, cf. Lidar et al. 2006). However, Lundqvist and colleagues emphasized the importance of analyzing epistemological moves in situ, since per Wittgenstein, the meaning of such moves is contextual:

> In a different situation, the same kind of epistemological move might have a completely different meaning. This design accords with Wittgenstein's methodological advice, which is to *look* at the circumstances in which words and sentences are used (e.g., Wittgenstein, 1953/2001: §66, 1969: §501). (Lundqvist et al. 2009, p. 864, emphasis in original)

With an understanding of students' practical epistemologies and teachers' epistemological moves in hand, CACM was used to uncover the local norms at play in the science classroom and then "to identify and problematize norms as resources in the practice studied, as well as constituting specific worldviews and being potential consequences of students' socialization" (Lundqvist et al. p. 865). Through actual analysis of empirical materials, Lundqvist and colleagues showed how naïve empiricist and naïve rationalist views of science may be at play in classroom science lessons, a result that "could attract considerable criticism" for the way in which it contradicts "many countries' policy documents with regard to how to portray science and its activities" (p. 870).

In these many ways, Wittgenstein's corpus has thus served as an inspiration to science educators seeking new ways of researching learning in science, not just in the theoretical assumptions made about learning, but in actual analytic practices. Wittgenstein has been read as telling us to focus our efforts on describing language use in practice. He has also been interpreted as authorizing an analysis of meanings that stand fast versus those which must be resolved through building relations. In this way, educators have used Wittgenstein's philosophy to first describe classroom life on a micro-interactional scale and in some cases to use these descriptions to answer larger questions about science education or learning.

43.3.5 Summary

The discussion above is not exhaustive with respect to Wittgenstein's influence in science education research; others have considered the implications of the *Tractatus* in science education (e.g., Besson 2010; Rowlands et al. 2007) or the import of Wittgenstein's concepts for NOS pedagogy (e.g., Irzik and Nola 2011). But this chapter's focus is on the ways in which Wittgenstein's later writings have informed our conceptions of and research on students' science learning. The impact of Wittgenstein's philosophy in science education, while certainly not ubiquitous, can be seen in substantial strands of argument across the literature of the last 20 years. First, Wittgenstein was influential in a shift among science educators away from a singular definition of rationality as it relates to knowledge, learning, and particularly scientific rationality. Second, Wittgenstein is often invoked by researchers who aim to study learning from a sociocultural and discursive perspective. His notion of "language games" helped researchers transition from thinking of conceptual understanding as "the acquisition of mental schema" to conceiving of it as "the ability to use language correctly in various contexts." Wittgenstein was tangentially influential in the movement that sought to build studies of science classroom learning in the model of sociological studies of professional laboratory science, since his philosophy was central to the science studies movement itself. Finally, researchers have used Wittgenstein's philosophy to argue for a different model of analysis, for example, studies that focus on description and studies that focus on the ways in which words do or do not "stand fast" in actual instances of talk.

43.4 A Critical Assessment of Wittgenstein's Role (So Far) in Science Education

The discussion so far suggests that many of the arguments or lines of inquiry introduced above tend to make use of Wittgenstein in "ordinary" ways, that is, as a source of analytic conceptual innovation for science education research investigations. Most of these projects use Wittgenstein in ways that are familiar in our pursuit of new topics or distinctions. But when we read Wittgenstein as yet another resource or authority for speaking differently, we may risk missing what he has to say, as a program aimed at rewriting the very terms of doing philosophy. In this way, straying from Wittgenstein's disciplined form of analysis is not difficult to do. Indeed, whether one has or not is a central contest in the commentaries on his corpus.[9] In this light, it is a virtual certainty that inconsistencies can be found in treatments of Wittgenstein's work in science education. Often we see them within paragraphs, or even sentences, of suggestions for following Wittgenstein's insights as questionable formulations of the implications of these insights. This is not necessarily because specific passages or citations are misunderstood. To the contrary, Wittgenstein *does* talk about the meaning of a word being its use in a language game or the impossibility of a private language, for example.

However, a major source of incongruity is the difference between Wittgenstein's project – his method of doing philosophy "as therapy" – and the project that drives most work in science education. For Wittgenstein, the goal of philosophy is to untangle conceptual confusions. His writings critique the very enterprise of philosophy as we know it, a reading that is very difficult to find in science education. In education research, the identifying task is to build a scientific account of various aspects of the educational experience, e.g., a theory of learning that can explain and predict human action or at least the acquisition of scientific understanding. Yet it is just this kind of theory building that was a target of Wittgenstein's efforts at conceptual clarification; it was precisely these "totalizing" accounts and ambitions that he was dissolving. What Wittgenstein pointed to over and over again in his work was our tendency to theorize the world and to inflate otherwise ordinary words so as to appear extraordinary and foundational. It was the pursuit of such foundations that he was inveighing against; he was writing a critique of the very possibility:

> When philosophers use a word – "knowledge," "being," "object," "I," "proposition," "name" – and try to grasp the *essence* of the thing, one must always ask oneself: is the word ever actually used in this way in the language-game which is its original home? –
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> What *we* do is to bring words back from their metaphysical to their everyday use. (Wittgenstein 1958, §116, emphasis in original)[10]

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[9] For instance, see Malcolm (1989) and Baker and Hacker (1990); or see Sharrock and Button (1999) on the Lynch-Bloor exchange cited earlier.

[10] Note also the use of "language game" in this passage: not as a theoretical imperative but something mundane and ordinarily recognizable.

Wittgenstein's recommendation for science education researchers, then, would undoubtedly have been to step back and "battle against the bewitchment of our intelligence by means of language" (Wittgenstein 1958, §109). The "bewitchment" will not be broken by the introduction of new topics, but rather by an examination of old habits, and especially those deeply taken for granted in grammatical confusions.

43.4.1 "Meaning" as a Source of Conceptual Confusion

Although there are many candidate terms in this battle, "meaning" seems to cast a particularly charming spell on contemporary theories of learning. This handbook chapter has focused on the ways in which Wittgenstein's writings have been used in research on learning in science; all of it are in some way connected to accounts of meaning. Meaning is subject to local forms of rationality, which must be investigated empirically, uncovered, and articulated. The concept of "language game" serves as an alternative to "mental images," as a vehicle through which meaning is constructed or conveyed. "Meaning-in-use" usually refers to the performative and public nature of meaning; however, the contextual and temporary nature of meaning is also often linked to this phrase as well. Meanings that "stand fast," according to the use of this expression in science education, are those that are not questioned during talk.

In science education research, each of the above concepts or phrases associated with Wittgenstein's philosophy has been pressed into service on behalf of a driving interest in students' meaning making. "Meaning making" typically refers to a notion that the meanings of words or expressions are constructed or created via a process involving an interaction between prior understanding and engagement with new phenomena, whether those phenomena are physical or discursive. The picture is something like this: meanings result from engaging in practices; or, people assign meanings (typically, to words or perhaps gestures in discourse) as an outcome of interacting with others and/or the physical world. Alternatively, one might say that for science education researchers, meaning making involves a process of verifying and then attaching or assigning an ostensive definition to a "concept," whether this concept is said to be located in discourse or in mental schema.

To wit, Kelly and Green (1998) write, "Members of a group ascribe meaning to the processes, artifacts, practices, and signs and symbols that they construct in and through everyday activity" (p. 147). And Wickman (2004) notes of his "practical epistemology analysis" methodology that "The focus here is…to use a formal theory of meaning-making in illuminating the *connection* between *how* people produce meaning and *what* meaning is produced in a specific practice" (p. 327, emphasis in original). Lidar et al. (2010) outline the basic analytic practice:

> An encounter is where meaning making happens…The meaning-making process is thus analyzed by studying encounters where gaps could occur, and how people to fill the gaps, establish relations between the new in an encounter, and what stands fast. Biesta and Burbules (2003, p. 36) describe meaning making as "the way in which the organism responds to the environment." In practical epistemology terminology, this could be expressed: Meaning making is to create relations between the new in an encounter and what is standing fast. (p. 694–695)

In this way, Wittgenstein's philosophy has been tied to a generally "constructivist" logic of meaning making in science education, where uncertainty is continuously resolved by individuals linking their objects of inquiry to known meanings and/or objects in the environment. And the study of meaning, on this view, is rightfully an empirical investigation of "how" people make meaning and "what" meanings they make.[11]

However, from a Wittgensteinian viewpoint, this picture of meaning making in science education is entirely misleading. Again, recall that Wittgenstein championed seeking conceptual clarity about the terms which scholars were routinely tempted to use in a theoretical way. Thus, as an alternative to taking an unquestioned empirical interest in "meaning," we may first want to grasp – conceptually – the way in which we might think of the term. Recall Hacker's summary of Wittgenstein's philosophy in this regard:

> The meaning of an expression, with marginal qualifications, is its use. It is also what is understood by anyone who understands or knows what an expression means. And it is what is given by an explanation of meaning. An explanation of meaning, even a humdrum explanation given by means of a series of examples, is a rule – a standard of correctness – for the use of the explanandum. (Hacker 2007b, p. 4)

Wittgenstein's philosophy implies that "meaning" is something we should think of as *conventional* and in that sense *stable*, not arbitrarily "made" (or constructed) on the spot, as a result of some kind of process. What is meant by "meaning" in our ordinary, everyday discourse is not mysterious or in need of scientific explanation. When we are uncertain of the meaning of an expression, we find recourse in exemplars that illustrate its use; in other words, the meaning of an expression can be sought in imagining its typical use in language.

Now, of course, an expression can be misunderstood by or unfamiliar to persons or groups of persons. The meaning of an expression can change, or new expressions with new meanings can be created for specific purposes. These can, over time, become convention. And certainly, one can use double entendres, puns, or other wordplay to joke about meanings – but again, these too are orthodox. "Being ironic" on the one hand, or "getting the joke" on the other, in fact depends on the conventional nature of meaning. But these examples license neither the picture of a general, pervasive process of "meaning making" nor a science which seeks to explain individual (or community) engagement in a constant skeptical inquiry

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[11] Does conceptualizing meaning making as being "social" change its nature for the purposes of empirical investigation? Kelly and Crawford (1997) state: "We view meaning as of a group, not an individual, and therefore view the substance of cognition as social (Wittgenstein 1958)" (p. 536). Social constructivism is often based on the view – said to be taken from Wittgenstein – that groups "make meaning" by creating rules for using expressions (and this is the process to be empirically investigated; cf. Bloor 1983). On this point, Sharrock and Button's (1999) and Francis's (2005) critiques of Bloor's program are instructive. Briefly, constructivism treats consensus as a precondition of rule following (and thus in need of explanation) rather than seeing the regular agreement about meaning as part of the use of language in our lives (see also Richter 2004; similarly Diamond 1989; Lynch 1992a). In this way, social constructivism shares with "individual" constructivism the same wrong-headed view of meaning as resulting from a process that requires theoretical explanation.

with the world, pursuing a means of anchoring words with meanings in order to proceed with learning (or even with basic communication).[12]

In other words, a first distinction to be drawn here is between "meaning" as an object of empirical analysis and "meaning" as we might *ordinarily* think of it: We ask the meaning of an unfamiliar word or expression we encounter in everyday life, and it is explained to us via examples or definition. Ryle similarly deflates the meaning of "meaning": "To know what an expression means involves knowing what can (logically) be said with it and what cannot (logically) be said with it. It involves knowing a set of bans, fiats and obligations, or, in a word, it is to know the rules of the employment of that expression" (1971, p. 363).

And there is a second sense in which to think of "meaning" as knowing how to use an expression. It is helpful to understand the context of Wittgenstein's words and that they took place in a larger discussion about other notions of what "meaning" might be. In part, what Wittgenstein was doing in emphasizing meaning-in-use was contrasting this with a notion that the meaning of a word or expression is identical with the object denoted by it (cf., Ryle 1971). Richter (2004) notes that "the main rival views" to be contrasted with Wittgenstein's notion of meaning-in-use were "that the meaning of a word is some object that it names" or "that the meaning of a word is some psychological feeling" (no page number). In other words, Wittgenstein was drawing a distinction between meaning as *doing* and meaning as *representing*. He was critiquing representational notions of language. Yet analytic orientations in science education that theorize meanings as being "assigned to processes, artifacts, practices, and signs and symbols" or meaning making as consisting in construing relations between concepts return us to a picture of "meanings" as representational "links" – between the world and talk and between known and new. Of course, explaining the meaning of a word *can* consist in giving an ostensive definition. But Hacker reminds us of the proper way to think about an ostensive definition, which is "*not [as] a link* between word and object, or language and reality, but a rule for the use of a word" (Hacker 2007b, p. 4, emphasis added). Again, Ryle is useful here: "the meanings or significations of many kinds of expressions are matters not of *naming* things but of *saying* things" (1971, p. 362, emphasis in original).

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[12] Here it is instructive to consider how the science studies literature has been looked to as exemplary of studying new meaning creation. Specifically, Garfinkel et al. (1981) study of the discovery of an optical pulsar has been recommended as a model for the study of "the processes by which scientific objects are discursively created" (Kelly and Crawford 1997, p. 535) and thus for how the "school science knowledge creation" of classroom cohorts may be similarly examined. This tendency to link science studies and research in science education perhaps stems from our history of connecting our understanding of how scientists create knowledge to how people create meaning (e.g., a la conceptual change and various constructivist theories of science learning). But Garfinkel, Lynch, and Livingston's examination of talk recorded during the optical pulsar discovery occurred *after* the event had been taken up and affirmed within the relevant science community. With hindsight the "night's work" can get flagged as the "origin" (or part of the origin) of a new conventional understanding about pulsars, but we shouldn't then imagine that new meanings are created this way in *every* lab encounter. Neither should we focus on students' ordinary science classroom interaction as an incessant creation of new meanings. See Greiffenhagen and Sherman (2008) on the problem with conceiving of students' knowledge of the natural world as having "the form of a systematic, causal (proto-scientific) theory" (p. 16).

The upshot of these considerations is that science educators' efforts to explain "meaning making" appear misguided, especially among those who find instruction in Wittgenstein's later works. The nature of "meaning" is not mysterious when we consider its ordinary use. Meanings are not connections, associations, names, or links between language and the world. In contrast to the prevailing *theoretical* orientation, when we *ordinarily* focus on meanings, we focus on their conventional nature; we focus on the typical rules for using an expression, and not on how meanings might be idiosyncratically "made" by individuals or groups. In short, there is no empirical imperative for the study of meaning making because there is no general, overarching *process* at play in need of explanation.

43.4.2 Meanings "Standing Fast"

Yet, the impulse to explain in matters of meaning persists, perhaps most vividly among the advocates of practical epistemology analysis. Practical epistemology analysis theorizes just such a process and turns on Wittgenstein's notion of "standing fast" to anchor it. Wickman (2004) proposes that when "a word is 'clearly understood' in a specific language-game [it] can be operationalized as 'standing fast,' which means that it can be seen to be used without hesitation or questioning" (p. 328). Words that do stand fast act as anchors to those that do not; and by establishing these different standings, we can examine how new meanings can be created. In other words, "standing fast" is the marker of certain knowledge, and sequences in which students speak without running into apparent difficulty are taken as evidence for words – and therefore meanings – "standing fast."

But, in what context was Wittgenstein using the phrase "standing fast"? The passage from *On Certainty* cited by Wickman and Östman (2002b) reads:

> The child learns to believe a host of things. I.e. it learns to act according to these beliefs. Bit by bit there forms a system of what is believed, and in that system some things stand unshakeably fast and some are more or less liable to shift. What stands fast does so, not because it is intrinsically obvious or convincing; it is rather held fast by what lies around it. (Wittgenstein 1969, §144)

On the surface, it seems reasonable that these remarks could leverage the kind of methodology developed as "practical epistemology analysis": find out what students seem to know and not know as evidenced in their ways of speaking, and investigate what lies around it to make this knowledge certain (or not).

But importantly, this passage is actually part of a larger argument that Wittgenstein is making about the nature of certainty and doubt. He was drawing a contrast between words that *stand fast* and ones that are *known* or *learned*. Quoting at length from *On Certainty* illustrates more of this context:

> How does someone judge which is his right and which is his left hand? How do I know that my judgment will agree with someone else's? How do I know that this color is blue? If I don't trust myself here, why should I trust anyone else's judgment? Is there a why? Must I not begin to trust somewhere? That is to say: somewhere I must begin with not-doubting; and that is not, so to speak, hasty but excusable: it is part of judging.

> I should like to say: Moore does not *know* what he asserts he knows, but it stands fast for him, as also for me; regarding it as absolutely solid is part of our *method* of doubt and enquiry.
>
> I do not explicitly learn the propositions that stand fast for me. I can discover them subsequently like the axis around which a body rotates. The axis is not fixed in the sense that anything holds it fast, but the movement around it determines its immobility.
>
> No one ever taught me that my hands don't disappear when I am not paying attention to them. Nor can I be said to presuppose the truth of this proposition in my assertions etc., (as if they rested on it) while it only gets sense from the rest of our procedure of asserting. (1969, §150–153, emphasis in original)

Wittgenstein is calling attention to the skepticist's quest for a formal grounding of our knowledge. How do we know we have a body? How do we know that my "blue" is your "blue"? and so on. Wittgenstein's Cambridge colleague G. E. Moore addressed philosophical skepticism by famously declaring that his hands exist because he knows they exist. But in the passage above (and throughout *On Certainty*), Wittgenstein questions the grammar of this assertion. He argues that "knowing" is sensible only when "not knowing" is possible; "Doubting and non-doubting behavior. There is the first only if there is the second" (Wittgenstein 1969, §354).

In the specific case of knowing one's hands exist, "If Moore were to pronounce the opposite of those propositions which he declares certain, we should not just not share his opinion: we should regard him as demented" (1969, §155). This is not to claim that it is impossible to imagine a context in which such a statement is coherent (e.g., as a joke or, more seriously, as being said by someone just awakening from a procedure where extremities had been amputated). Wittgenstein's point is that one does not generally consider possession of body parts to be in question. So, "standing fast" for Wittgenstein was an alternative way to describe what Moore said that he *knows* and an attempt to dispel the skepticist orientation altogether by illustrating that such a statement is not in need of any kind of grounding. Moore was looking for assurances that no actual language game needs.

With this very specific purpose for the use of the phrase "standing fast" in mind, it is difficult to support the interpretation of it being advanced in science education research. Since at least the work of Ausubel, educational theorists have been arguing that learning is a process of linking new knowledge to existing knowledge. "Practical epistemology analysis" represents a contemporary interpretation of this theory, more invested in language and social interaction than its predecessors, but still focused on the idea that knowledge must be secured in order for learning, or even communication itself, to take place. Wittgenstein on the other hand explicitly rejected a foundational view of knowledge in general:

> But since a language-game is something that consists in the recurrent procedures of the game in time, it seems impossible to say in any individual case that such-and-such must be beyond doubt if there is to be a language-game—*though it is right enough to say that as a rule some empirical judgment or other must be beyond doubt*. (1969, §519, emphasis added)

> A doubt without an end is not even a doubt. (1969, §625)

> For why should the language game rest on some kind of knowledge? (1969, §477)

Of course, there are often times in conversation when meanings are unclear, and it is sensible to suggest that students who encounter unfamiliar words or usages during a classroom task may infer meanings from more familiar terms. What Wittgenstein cautions against, as he is wont to do, is the idea that something like a linguistic gap-closing exercise is constitutive of *all* meaning and thus learning, let alone all use of language.

43.4.3 Meaning, Interpreting, and Understanding

The discussion above suggests that any program that aims to formally explain students' meaning making is ill advised. This seems to be Wittgenstein's counsel, though it may be a decidedly unsatisfactory conclusion for science education researchers. It is tempting to think that the matter has been oversimplified in this discussion by focusing on the ordinary and conventional notion of "meaning." After all, Wittgenstein also emphasized meaning-in-context, presumably pointing to the sometimes unexpected and unique use of words. Furthermore, science educators' interests in this regard are understandable, as students in the science classroom do not yet know the conventions of science or even school science. It could be argued that what we are really after in science education is how students *interpret* meanings in various contexts, and particularly in the classroom setting, e.g., how they interpret "gene" or "heredity." Certainly, we "interpret" the meaning of talk in interaction. This may be particularly true in instances when one encounters an unfamiliar expression, a likely occurrence in the science classroom. If our interest is not in meanings, do we instead need a series of empirical investigations and ultimately a theory to explain *interpretations*? In other words, perhaps the question is what *interpretations* are made by science students, and how are they made?

The Lidar et al. (2010) study of students' discussions about the earth's shape and gravity provides delightful examples of what could be construed as novices' interpretive work. When asked "If you were to walk for many days in a straight line, where would you end up?" some second, fourth, and fifth grade students were able to produce the sought-after answer; one would end up back where he or she started. But other students mention running into a house or the ocean. And one group of students finds a "straight" road outward from their town on a map and "walks" along it with their fingers for "20 steps" to arrive at an answer to the question. The latter group's answer to the question is unique and unexpected – but is being able to explain and predict an occurrence like this the goal of our empirical investigation of science learning? Is explaining and predicting such interpretations even possible?

Again, we can examine Wittgenstein's writings for some guidance. In the case of learning a new meaning, he discusses how ostensive teaching can be variously interpreted:

> Let us then explain the word 'tove' by pointing to a pencil and saying 'this is tove'…Now the ostensive definition 'this is tove' can be interpreted all sorts of ways…The definition can then be interpreted to mean:
>
> "This is a pencil",
> "This is round",
> "This is wood",
> "This is one",
> "This is hard," etc., etc. (Wittgenstein 1960, p. 2)

In other words, it is entirely possible that even in the most basic of interactions – pointing and naming – interpretations of what is meant can be diverse. Nevertheless, none of these interpretations is unreasonable, and all point to a sensible conclusion reached from witnessing the pointing and talking described. The meanings of various interpretations of "tove" are *still* conventional. Likewise, the interpretations of some students in Lidar and colleagues' (2010) study may be unexpected, and while it is instructive for teachers to be aware of a range of possible student interpretations of questions asked in a classroom activity, it is difficult to know what about them is in need of explanation or what explanations set them apart.

The temptation of Wittgenstein's vignette about "tove," or a focus on it as a play on interpretation – and it is a dangerously compelling one – is to assume that *every* interaction in language consists in making an interpretation. Words or expressions *can* be interpreted, *but they don't have to be*. Here again is where we want to be reminded of Wittgenstein's philosophical project to "bring words back from their metaphysical to their everyday use" (Wittgenstein 1958, §116). Wittgenstein cautions against the tendency to assume that an interpretation always lies behind sense and meaning. He uses the example of the command "fetch me a red flower from the meadow" and asks, must one conjure up an image of a red patch and compare it to the flowers before him in order to comply with the order? In other words: must we interpret, e.g., "red" in order to obey the command? His clever response: "consider the order '*imagine* a red patch'" (Wittgenstein 1960, p. 3). What process is to be imagined here? Wittgenstein continues, "Now you might ask: do we interpret the words before we obey the order? And in some cases you will find that you do something which might be called interpreting before obeying, in some cases not" (1960, p. 3).

As with "meaning," it would appear that there is nothing foundational or extraordinary about "interpretation" that calls for empirical investigation and theory building. The astute reader will surmise that any next candidate term, once considered in the context of its typical use in the language, will be "deflated" in a similar way, e.g., understanding[13]:

> 'What happens when a man suddenly understands?' – The question is badly framed. If it is a question about the meaning of the expression 'sudden understanding,' *the answer is not to point to a process that we give this name to*. – The question might mean: what are the tokens of sudden understanding; what are its psychical accompaniments?…The question what the expression means is not answered by such a description; and this misleads us into concluding that understanding is a specific indefinable experience. (Wittgenstein 1958, §321–322, emphasis added)

> Trying to understand may involve (polymorphous) processes, but actually understanding is neither an act nor a process of any kind. We distinguish between thinking that one has understood and actually having understood: thus, understanding carries *no subjective sovereignty* for its claimant. Since understanding in these cases (we exempt the notion of 'empathy' here) does not designate *any* process, the notion that understanding speech is a matter of 'processing' it (the concept favored by cognitivists infatuated with computational jargon) cannot pass muster. (Coulter 2008, p. 28, emphasis in original)

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[13] Or, "learning" (Macbeth et al. 2011).

In light of these discussions, a conceptual analysis of "meaning" would seem to recommend that we not think of meanings as individually or situationally "constructed" as the product of some internal or social process or any combination of the two. The meaning of an expression can be interpreted, and people can understand or misunderstand an utterance. A particular expression can have different uses and thus different meanings. But meanings themselves are not "negotiated" or "assigned" in interaction, in the sense of having been created from an internal or external process that must then be explained. What we *can* do in conversation is to ascertain whether or not someone understands how to use an expression and whether someone (even ourselves) misunderstood what was expressed. But in ordinary life we don't make these assessments by looking "behind" or "underneath" talk for the meanings assigned to an expression, as if these were separate from the talk itself. Per Wittgenstein, "When I think in language, there aren't 'meanings' going through my mind in addition to the verbal expressions: the language is itself the vehicle of thought" (1958, §329). Or, as Coulter reminds us, "it is the scenic performance (or its possibility) which comprises the criterion for having understood something, not any phenomena postulated as 'internal' to the person" (2008, p. 28). In other words, we judge understanding or misunderstanding by linguistic performance, by whether or not someone has followed the correct rule for using an expression.

43.5 Conclusion

Wittgenstein's later philosophy has served to inspire new interest in language and thinking across the social sciences, and science education is no exception. Specifically in science education, Wittgenstein's writings have been used to argue for an alternate conception of rationality, to support theories examining the discursive and social nature of learning, to advocate for investigations of science classrooms that parallel ethnographic and sociological investigations of professional science labs, and to develop alternative research methodologies. And yet, this chapter has argued that efforts to merge concepts from Wittgenstein's philosophy into the typical project of science education research often can be misguided. Rather than understand Wittgenstein's writings as a penetrating critique of our familiar ways of doing "analysis," science education researchers have routinely attempted to recruit selected arguments and formulations for use in familiar programs of research. But this habit likely results in perpetuating conceptual confusions, if not introducing new candidates. Minar argues that "we cannot avoid thinking about [Wittgenstein's] methods and their rationale if we are to find his philosophy intelligible" (1995, p. 416). In the observation is a recommendation for how the science education literature might proceed differently with Wittgenstein's insights.

The "ordinary ways of researching" in science education are tied to a historical sense of the project of education research more broadly, which is to "scientize" teaching: education researchers essentially do what teachers do, but with the power of "theory" behind their judgments (cf. Sherman 2005). This urge to theorize was an anathema to Wittgenstein. In an extensive passage early in *The Blue and Brown Books*, he laments what he calls the "craving for generality" in academic endeavors[14]:

> Now what makes it difficult for us to take this line of investigation [i.e., Wittgenstein's philosophical method] is our craving for generality.
>
> This craving for generality is the resultant of a number of tendencies connected with particular philosophical confusions. There is—
>
> (a) The tendency to look for something in common to all the entities which we commonly subsume under a general term….The idea of a general concept being a common property of its particular instances connects up with other primitive, too simple, ideas of the structure of language. It is comparable to the idea that *properties* are *ingredients* of the things which have the properties; e.g., that beauty is an ingredient of all beautiful things as alcohol is of beer and wine, and that we therefore could have pure beauty, unadulterated by anything that is beautiful.
>
> (b) There is a tendency rooted in our usual forms of expression, to think that the man who has learnt to understand a general term, say, the term "leaf", has thereby come to possess a kind of general picture of a leaf, as opposed to pictures of particular leaves…. We say that he sees what is common to all these leaves; and this is true if we mean that he can on being asked tell us certain features or properties which they have in common. But we are inclined to think that the general idea of a leaf is something like a visual image, but one which only contains what is common to all leaves….This again is connected with the idea that the meaning of a word is an image, or a thing correlated to the word….
>
> (c) Again, the idea we have of what happens when we get hold of the general idea 'leaf,' 'plant,' etc. etc., is connected with the confusion between a mental state, meaning a state of a hypothetical mental mechanism, and a mental state meaning a state of consciousness (toothache, etc.).
>
> (d) Our craving for generality has another main source: our preoccupation with the method of science….Philosophers constantly see the method of science before their eyes, and are irresistibly tempted to ask and answer questions in the way science does.…I want to say here that it can never be our job to reduce anything to anything, or to explain anything. Philosophy really *is* 'purely descriptive'….
>
> Instead of 'craving for generality' I could also have said "the contemptuous attitude toward the particular case." (1960, pp. 17–18)

Taking up Wittgenstein's writings means seeing them in light of *his* project: to "bring words back from their metaphysical to their everyday use" (Wittgenstein 1958, §116). In science education, we see the tendencies toward generality described above in studies which aim to formally explain students' "meaning making," even in studies which purport to be informed by Wittgenstein's writings. An alternative program of analysis resting on "therapeutic" descriptions of the ordinary use of concepts has been suggested in the critiques advanced in this chapter.

Citing Norman Malcolm, Richter (2004) identifies four primary ways in which Wittgenstein's therapeutic method of philosophy could be employed: "describing circumstances in which a seemingly problematic expression might actually be used in everyday life, comparing our use of words with imaginary language games, imagining fictitious natural history, and explaining psychologically the temptation

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to use a certain expression inappropriately" (no page number). In the discussions above, an attempt has been made to contrast the use of "meaning" and related terms in science education research with their ordinary, mundane use in order to reconsider not only the topics of our research but the research program itself. Wittgenstein advocated a very different kind of descriptive enterprise.

It is important to clarify that in taking this position, Wittgenstein should not be seen as "antiscience" or "'anti-philosophy."[15] Scientific practice is completely appropriate for making sense of the natural world. What Wittgenstein is arguing is that the assumptions we make about the natural world in studying it the way we do are not assumptions we can make about the way language works; thus, the study of people is necessarily different from the study of the natural world (cf. Hutchinson et al. 2008; Winch 1958). Rather than aim for producing general theoretical explanations of human language-based action, we should aim for careful, patient examination and description of the use of concepts in our lives (cf., Diamond 1989).

> Here we come up against a remarkable and characteristic phenomenon in philosophical investigation: the difficulty—I might say—is not of finding the solution but rather that of recognizing as the solution something that looks as if it were only a preliminary to it….This is connected, I believe, with our wrongly expecting an explanation, whereas the solution to our difficulty is a description, if we give it the right place in our considerations. If we dwell upon it, and do not try to get beyond it.
>
> The difficulty here is: to stop. (Wittgenstein 1967, §314)

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[15] Of course, allowing that philosophy be understood as therapeutic conceptual analysis.

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Chapter 44
Science Textbooks: The Role of History and Philosophy of Science

Mansoor Niaz

44.1 Introduction

Gerald Holton's (1952) *Introduction to Concepts and Theories in Physical Science* provided a glimpse for students and teachers as to how science evolves through the interactions of theories, experiments, and the work of actual scientists within a history and philosophy of science (HPS) perspective. This textbook has been a source of inspiration for many students of HPS. Looking back after almost 50 years, Holton (2003) considered that the textbook facilitated understanding of science as a coherent story based on the thoughts and work of living scientists. More recently, a new edition of this textbook has presented science as a human adventure, from Copernicus to Einstein and beyond (Holton and Brush 2001).

Writing in a special issue dedicated to *Students' Models and Epistemologies of Science,* Linn et al. (1991) pointed out: "Gerald Holton infused Harvard Project Physics with marvelous historical examples of scientific investigation. These were heralded as ground breaking, but were rarely imitated. Instead, if they discuss process at all, *science textbooks describe an outmoded and incorrect view of scientific knowledge acquisition*" (p. 729, italics added). The importance of history and philosophy of science was generally recognized by science educators in the 1960s (Klopfer 1969; Robinson 1969), and in the last 20 years, there has been a worldwide sustained effort to provide a rationale for its inclusion in the science curriculum (Matthews 1990, 1994/2014; Scheffler 1992).

Many researchers and teachers have endorsed the inclusion of history and philosophy of science (HPS) in the science curriculum, textbooks, and classroom

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practice (Hodson 1985, 1988, 2008, 2009; Matthews 1994/2014, 1998; Niaz 2008, 2009a, b, 2011). Interestingly, however, Bevilacqua and Bordoni (1998) have stated: “We are not interested in adding the history of physics to teaching physics, as an optional subject: the history of physics is ‘inside’ physics” (p. 451). Guisasola et al. (2005) have endorsed a similar thesis. This is an important argument, which has generally been ignored in the science education literature and especially that related to textbooks. In other words, we do not have to justify or request for the inclusion of HPS in the science curriculum and textbooks. Teaching science without the historical context in which ideas and theories develop comes quite close to what Schwab (1962, 1974) has referred to as “rhetoric of conclusions.” Matthews (1998) has argued that philosophy is not far below the surface in any science classroom, as most textbooks and classroom discussions deal among others, with concepts, such as law, theory, model, explanation, cause, hypothesis, confirmation, observation, evidence, and idealization (p. 168). Similarly, Niaz and Rodríguez (2001) based on a historical framework have shown that HPS is already “inside” chemistry, and we do not need separate courses for its introduction.

At this stage it is important to clarify that the approach (HPS being inside the science curriculum) suggested here does not rule out the possibility of designing separate courses dealing with various aspects of the history of science both at the undergraduate and graduate level. It is worthwhile to provide here some examples of such an approach. Abd-El-Khalick (2005) explored the views of preservice science teachers by including a discussion of historical episodes such as dinosaur extinction controversy, Copernican revolution, Michelson-Morley experiment, cold fusion, and verification of the relativity theory. Pocoví (2007) studied the effect of history-based instructional material (Faraday’s writings) to facilitate freshman students’ understanding of field lines. Hosson and Kaminski (2007) developed a teaching strategy based on the history of the optical mechanism of vision (Alhazen’s writings) for facilitating high schools students’ reasoning about vision. Niaz (2009b) developed a course for facilitating in-service chemistry teachers’ understanding of nature of science by including historical controversies related to atomic models and the oil drop experiment. This clearly shows that the two approaches can be used to facilitate an understanding based on HPS.

Abd-El-Khalick (2005) has expressed the relationship between nature of science (NOS) and history and philosophy of science (HPS), in cogent terms:

> … if we want teachers to address NOS instructionally, our efforts to help them develop the necessary understandings need to go beyond a few hours of NOS-related instruction in a science- methods course. Naturally, history and philosophy of science, which are the ‘stuff’ of NOS, are primary candidates for enriching the development of science teachers in the area of NOS. (p. 38)

The role of history of science in science education and especially the textbooks has been the source of considerable discussion in the literature.[1] At this stage it is

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[1] For example, see Brush (2000), Bensaude-Vincent (2006), Chiappetta and colleagues (2006), Gooday and colleagues (2008), Kindi (2005), Niaz (2010a), Siegel (1978), and Zemplén (2007).

important to differentiate between two types of studies related to science textbooks that can be classified as:

(a) Domain specific: These studies are based on a historical reconstruction of a given topic of the science curriculum. The following are some examples of such studies presented in this chapter: quantum hypothesis (Brush 2000), photoelectric effect (Niaz et al. 2010a), periodic table (Brito et al. 2005), and atomic structure (Niaz 1998, 2000a; Justi and Gilbert 2000; Padilla and Furio-Mas 2008).
(b) Domain general: These studies are based on a series of nature of science (NOS) dimensions, which are in turn derived from the history and philosophy of science. Such dimensions consider NOS to be empirical, tentative, inferential, creative, theory driven, social, and culturally embedded. The following examples of this research are presented in this chapter: Abd-El-Khalick et al. (2008) and Leite (2002).

Although there is an overlap between these two types of studies, the distinction between the domain specific and domain general is important. Domain-general dimensions can be used to evaluate various parts of the textbooks, irrespective of the science content selected. In contrast, domain-specific studies are based on a historical reconstruction of a topic, and, for example, criteria developed for atomic structure cannot be used for evaluating the photoelectric effect.

Purpose of this chapter is to review research based on analyses of science textbooks that explicitly use a history and philosophy of science framework. This review has focused on studies published in the 15-year period (1996–2010) and has drawn on the following major science education journals: *International Journal of Science Education, Journal of Research in Science Teaching, Science Education,* and *Science & Education.* In order to select a study for review, I used the following list of criteria: title of the article, abstract, keywords, theoretical rationale, method, conclusion, and references. Furthermore, it was not just one criterion or certain terms but rather the overall contribution of the study towards facilitating an understanding of the science topic, within an HPS perspective that determined its selection. It is important to note that there are some issues such as science literacy, science-technology-society (STS), conceptual change, pedagogical content knowledge, analogies, and constructivism which are important within an HPS perspective. However, articles related to such issues were included only if they had an explicit bearing on some aspect of HPS and thus facilitated greater understanding. Based on these criteria 52 articles were selected for review, and Table 44.1 provides a distribution of the articles based on the year of publication and the journal. Table 44.2 provides a distribution of the selected articles according to the following subjects: biology, chemistry, physics, and school science. It can be observed that over half the studies(28 out of 52) were published in *Science & Education*, which clearly shows the importance of HPS for this journal. In the following sections discussion of each of these studies is presented. Table 44.2 shows that 19 studies dealt with school science (primary, secondary, and high school). However, 15 of these studies explicitly dealt with biology, chemistry, and physics textbooks at the high school level and hence were discussed along with other studies in these subjects.

Table 44.1 Distribution of articles based on textbooks published in major science education journals*, 1996–2010 (n = 52)

	Number of articles			
Year	IJSE	JRST	SE	S&E
1996	–	1	1	1
1997	–	1	–	–
1998	–	1	1	–
1999	1	–	2	1
2000	4	1	–	2
2001	3	–	–	3
2002	–	–	–	3
2003	–	–	–	3
2004	–	–	–	–
2005	1	1	–	5
2006	–	–	–	1
2007	1	–	–	3
2008	1	1	–	3
2009	1	–	1	1
2010	–	–	1	2
Total	12	6	6	28

IJSE international journal of science education, *JRST* journal of research in science teaching, *SE* science education, *S&E* science & education

Table 44.2 Distribution of articles according to subject published in major science education journals, 1996–2010 (n = 52)

Subject	n	Articles
Biology	2	Flodin (2009), Hofmann and Weber (2003)
Chemistry	14	Brito et al. (2005), De Berg (2006), De Berg (2008a), De Berg (2008b), Furió-Más et al. (2005), Niaz (1998), Niaz (2000a), Niaz (2001a), Niaz (2001b), Niaz and Fernández (2008), Niaz and Rodríguez (2005), Padilla and Furió-Más (2008), Rodríguez and Niaz (2002), Schwartz (1999)
Physics	17	Arriassecq and Greca (2007), Assis and Zylbersztajn (2001), Brush (2000), Coelho (2010), Cotignola et al. (2002), Galili (2001), Galili and Tzeitlin (2003), Gilbert and Reiner (2000), Guisasola et al. (2005), Niaz et al. (2010a), Niss (2009), Pocoví and Finley (2003), Tampakis and Skordoulis (2007), Tarsitani and Vicentini (1996), Treagust and Harrison (2000), Velentzas et al. (2007)
School science	19	Abd-El-Khalick et al. (2008), Barberá et al. (1999), Chiappetta and Fillman (2007), Dagher and Ford (2005), De Posada (1999), Furió et al. (2000), Gardner (1999), Gericke and Hagberg (2010), Irez (2009), Justi and Gilbert (2000), Knain (2001), Koliopoulos and Constantinou (2005), Leite (2002), German et al. (1996), Milne (1998), Moody (1996), Shiland (1997), Skoog (2005), Van Berkel et al. (2000)

Notes

1. Textbooks included in the subjects of biology, chemistry, and physics are based on university freshman or higher levels
2. Textbooks included in the subject of school science are based on primary, secondary, or high school textbooks in biology, chemistry, and physics

44.2 University and High School Biology Textbooks

According to Chiappetta and Fillman (2007): "For over half a century, high school biology textbooks have played a critical role in science education because most students enroll in this course and use the adopted textbook that is a central component of the curriculum" (p. 1848). Similarly, Bybee (1989) has emphasized the role of textbooks in reforming biology education.

Chiappetta and Fillman (2007) analyzed five best-selling high school biology textbooks published in the USA (2002–2004), in order to study the inclusion of the following four NOS aspects: (a) science as a body of knowledge, (b) science as a way of investigating, (c) science as a way of thinking, and (d) science and its interactions with technology and society. These authors discuss the issue of inter-coder agreements and analyzed a much larger sample (than the 5 % in previous studies) of the textbooks from the following major topics: methods of science, ecology, cells, heredity, DNA, and evolution. It is concluded that these textbooks have a better balance of presenting the four NOS aspects as recommended by the reform documents (AAAS 1989; NRC 1996) than a previous study conducted 15 years ago, especially with regard to devoting more text to engaging students in finding out answers and learning how scientists do science.

Nature of science as depicted in five Turkish secondary school biology textbooks was studied by Irez (2009). These textbooks were widely used and published in the period 2006–2007. The following 11 themes regarding NOS were identified: description of science, characteristics of scientists, scientific method, empirical NOS, tentative NOS, nature of scientific theories and laws, inference and theoretical entities in science, subjective and theory-laden NOS, social and cultural embeddedness of science, and imagination and creativity in science. Based on these themes, the author also generated cognitive maps regarding NOS that provided an overall picture of how science was described in each textbook. Results obtained revealed that discussions regarding NOS represented a very small part of the textbooks and science was generally portrayed as a collection of facts and not as a dynamic process of generating and testing alternative explanations about nature. Of the 11 NOS themes studied, the author considered the following to be particularly misrepresented: scientific method and the tentative nature of scientific knowledge.

Coverage of human evolution in high school biology textbooks published in the USA (1900–2000) has been studied by Skoog (2005). Despite the sequencing of the human genome (Roberts 2001), human evolution continues to be a controversial topic in most parts of the world. Mayr (1997) has expressed this dilemma within a historical perspective: "No Darwinian idea was less acceptable to the Victorians than the derivation of man from a primate ancestor" (p. 25). Taking a longitudinal approach, Skoog has analyzed 113 high school textbooks in the following time periods: (a) 1900–1919 (n = 8): Only two textbooks stressed the validity of evolution. However, none of the textbooks contained material on human evolution or human fossil record. (b) 1920–1929 (n = 14): Five of the textbooks included some material concerned with human evolution and the human fossil record. The uniqueness of humans was noted in 11 of the 14 textbooks. This period was also characterized by widespread attempts to ban the teaching of evolution or its inclusion in textbooks. (c) 1930–1939 (n = 15): Four textbooks provided brief passages regarding human evolution. Discussions of the human fossil record were found in six textbooks. (d) 1940–1949 (n = 15): As compared to the previous time periods, these textbooks emphasized evolution to a greater extent. However, five textbooks failed to include any material on human evolution. (e) 1950–1959 (n = 15): Overall, eight textbooks lacked a discussion on both human evolution and the fossil record. According to Skoog (2005) this lack could be attributed to the following: "The 1950s were characterized by growing social unrest and insecurity as the Cold War and anti-communist fervor were building. Communism was associated with godlessness as was evolution by some" (p. 404). (f) 1960–1969 (n = 17): This period saw the publication of three textbooks and their revised editions, funded by the National Science Foundation under the auspices of the *Biological Science Curriculum Study* (BSCS). These textbooks gave unprecedented emphasis to human evolution, and this led the competing publishers to follow suit. (g) 1970–1989 (n = 17): Due to legislative attempts in various states to gain equal time for creationism, the unprecedented emphasis given to evolution did not continue in this period. Even the new versions of BSCS textbooks were characterized by less directness and certainty with respect to human evolution. (h) 1990–2000 (n = 12): Overall, the textbooks representing this period emphasized human evolution in a very comprehensive manner. Following N. Bohr, who considered science to be "the gradual removal of prejudice," Skoog (2005) concluded: "It is imperative that policy-makers, administrators, teachers, authors, and publishers work together to provide biology textbooks … [an opportunity] … to pursue the 'removal of prejudices' in the future citizens of America" (p. 419).

The study by Hofmann and Weber (2003) was included as it critiques Wells (2000), which is often cited by creationists who object to evolution in the science curriculum. Furthermore, Wells evaluated 10 science textbooks with respect to the notion of "universal common ancestry," and all textbooks that considered common descent as a "fact" were poorly graded. Hofmann and Weber (2003) have argued that fossil and molecular evidence is more than sufficient to warrant science educators to consider common descent as a well-established scientific fact.

According to Moody (1996) exposition of evolutionary theory in secondary school biology textbooks published in the USA has been adversely affected due to the influence of some nonscientific beliefs in the general public. Reviewing previous research on this topic, the author points out that it has been primarily concerned with measuring the quantity of space devoted to evolution in such textbooks during several decades. In contrast, the present study devised procedures to assess the overall role of evolution in the structure of the textbook. Results obtained revealed that the role of evolution in textbooks published in the 1990s increased considerably. This coincides with the results of Skoog (2005) who also reported a similar comprehensive increase in the coverage of evolution. Skoog, however, does not cite the work of Moody (1996).

German et al. (1996) analyzed nine high school biology laboratory manuals, published in the USA, during the period 1986–1993, to assess the promotion of scientific inquiry. It was hypothesized that open-ended laboratory activities (including pre-laboratory) which stress process skills reflect the nature of science more accurately. Inventory used for evaluating laboratory manuals was based on the following topics of the biology curriculum: cell structure, diffusion/osmosis, fermentation/cell respiration, leaves, tropisms, circulation, respiration, learning/behavior, hormones, and field studies. Authors used inter-rater agreements to establish the reliability of the inventory. Results of this study indicated that in general, high school biology laboratory manuals are highly structured in that they provide step-by-step detailed instructions. These manuals seldom provided opportunities for students to pose a question to be investigated, formulate a hypothesis to be tested, predict experimental results, work according to their design, or formulate a new question based on their own investigation.

Barberá and colleagues (1999) have traced the developments in the Spanish biology curriculum in the twentieth century (period of 100 years) based on the official publications of the nine national curricula and main textbooks used in this period. The main objective of the study was to focus on the relationship between socially controversial biological issues and the decision making procedures used by the different Spanish governments. Special attention was given to one of the most sensitive issue in biology education, namely, teaching of evolution. Authors found the political, social, and religious beliefs held by powerful and influential social groups to be particularly important in the elaboration of curriculum guidelines for socially controversial issues. It was concluded that such studies provide the necessary background for understanding biology education and its future development.

It seems that evolution is one of the most difficult and controversial topic of biology textbooks. Interestingly, its coverage in textbooks varies according to the prevailing sociopolitical environment. For example, during the cold war (1950s), the coverage of evolution decreased in textbooks published in the USA. Similarly, in Spain the coverage of evolution seems to depend on the political, social, and religious beliefs of influential social groups. A recent review has endorsed similar difficulties in teaching evolution (Smith 2010).

Flodin (2009) has studied different meanings of the gene concept within different subdisciplines in one biology textbook (Campbell and Reece 2005). This textbook is considered to be the most widely used English language science textbook in the world. According to the publisher it has reached two-thirds of all biology students in the USA. The author found the following interpretations of the gene concept in the textbook, depending on the subdiscipline: a trait (transmission genetics), an information structure (molecular biology), an actor (genomics), a regulator (developmental biology), and a marker (population genetics). These different functions of the gene concept are intermingled in the textbook, and the differences are not dealt with explicitly. The author concluded that such presentations in biology textbooks can become an obstacle to understanding for students and teachers. Findings of this study clearly show the importance of alternative interpretations of the gene concept and the need for a better explanation. Furthermore, it appears that textbook analyses are important and can improve even “the most widely used English language science textbook in the world.”

Conceptual variation in the depiction of gene function in upper secondary school biology and chemistry textbooks was studied by Gericke and Hagberg (2010). The study is based on 20 textbooks published in different countries (Sweden = 13, Australia = 2, Canada = 2, the UK = 2, the USA = 1). Of the 13 textbooks from Sweden, five were chemistry textbooks, as genetics forms part of the chemistry syllabus. The phenomenon of gene function can be described with multiple models, such as Mendelian, classical, biochemical classical, neoclassical, and the modern. Each of these models can be characterized by various epistemological features. Authors used content analysis (including inter-coder agreements) to determine the degree to which the epistemological features are represented in the subject matter and the five historical models. Results obtained revealed that most textbooks adopted a holistic approach that integrated various scientific frameworks, while ignoring conceptual variation and incommensurability between multiple models. It is concluded that such presentations can lead to cognitive conflicts for both the students and teachers, especially if they lack adequate knowledge of history and philosophy of science.

44.3 University and High School Chemistry Textbooks

Van Berkel and colleagues (2000) have explored the *hidden structure* of school chemistry based on the following research questions: (a) Why school chemistry textbooks from different countries look so remarkably similar? (b) What does the school chemistry curriculum look like? (c) Why is school chemistry so resistant to reforms? On the basis of content analysis of school chemistry textbooks (published in the Netherlands and UK) and syllabi, these authors have identified school chemistry as a form of normal science education (NSE), which is in turn based on Kuhn’s “normal science.” NSE is considered to be “dangerous” in that it isolates the learner from the history and philosophy of science and, as such, is narrow and rigid and tends to instill a dogmatic attitude towards science. The role of Kuhn’s normal science has been the subject of considerable research in science education and the analyses of science textbooks (Niaz 2011; Siegel 1978). Interestingly, Kuhn himself was somewhat ambiguous with respect to the relationship between NSE and science textbooks. Nevertheless the following statement from Kuhn (1977) is quite illustrative of the dilemma involved:

> The objective of a textbook is to provide the reader, in the most economical and easily assimilable form, with a statement of what the contemporary scientific community believes it knows and of the principal uses to which that knowledge can be put. *Information about how that knowledge was acquired (discovery) and about why it was accepted by the profession (confirmation) would at best be excess baggage. Though including that information would almost certainly increase the ‘humanistic’ values of the text and might conceivably breed more flexible and creative scientists*, it would inevitably detract from the ease of learning the contemporary scientific language. (p. 186, italics added)

This clearly shows that despite Kuhn's extraordinary contribution to HPS, he was perhaps not in tune with respect to how inclusion of HPS in science textbooks could invigorate students' and teachers' understanding of science.

Abd-El-Khalick and colleagues (2008) have drawn attention to the importance of including nature of science (NOS) in high school chemistry textbooks. These authors analyzed 14 textbooks (published in the USA, 1966–2005) including five "series" spanning one to four decades, with respect to the following NOS aspects: empirical, tentative, inferential, creative, theory driven, myth of the scientific method, nature of scientific theories and laws, and the social and cultural embeddedness of science. Based on the scoring rubric designed for this study, all three authors analyzed all textbooks independently and attained an inter-rater agreement of 86 %. Results from this study revealed that high school chemistry textbooks fared poorly in their representation of NOS, which led the authors to conclude: "These trends are incommensurate with the discourse in national and international science education reform documents (AAAS 1989; NRC 1996) …" (p. 835). Authors considered the following finding to be the most disturbing: All textbooks (except Toon et al. 1968) espoused the diehard myth of the "scientific method" (p. 848). Interestingly, Niaz and Maza (2011) in a study designed for evaluating nature of science found that Toon and Ellis (1978) had the highest score in a sample of 75 general chemistry textbooks. Abd-El-Khalick and colleagues (2008) refer to this as an "author effect" as compared to a "publisher effect." In other words science educators could approach textbook authors with well-formulated and documented arguments so as to facilitate the inclusion of such facets of NOS and HPS in their textbooks.

Justi and Gilbert (2000) analyzed high school chemistry textbooks (nine from Brazil and three from the UK, published 1993–1997) to study the presentation of atomic models. These authors report the use of hybrid models in textbooks based on various historical developments, such as Ancient Greek, Dalton, Thomson, Rutherford, Bohr, and quantum mechanics (Schrödinger's equation). Hybrid models do not provide students an opportunity to understand the dynamical nature of science, in which different approaches to understand phenomena are contrasted and critiqued. The authors concluded: "Hybrid models, by their nature as composites drawn from several distinct historical models, do not allow the history and philosophy of science to make a full contribution to science education" (p. 993).

Based on a historical reconstruction of the atomic models of Thomson, Rutherford, and Bohr, Niaz (1998) has analyzed 23 general chemistry textbooks published in the USA (1971–1992). All textbooks were evaluated on eight criteria which were validated by inter-rater agreements. Results obtained revealed that most textbooks emphasize experimental details based on observations, leading to the presentation of scientific progress as a *rhetoric of conclusions* (Schwab 1962), based on irrevocable truths. Such presentations in textbooks lack the conceptualizations of *heuristic principles* that led the scientists to design and interpret their experiments. For example, one of the criteria dealt with the Thomson-Rutherford controversy with respect to the single/compound scattering of alpha particles. Both Rutherford (1911) and Thomson performed similar experiments on the scattering of alpha particles, but their interpretations were entirely different. Thomson propounded the hypothesis of *compound scattering*, according to which a large angle deflection of an alpha particle resulted from successive collisions between the alpha particles and the positive charges distributed throughout the atom. Rutherford, in contrast, propounded the hypothesis of *single scattering*, according to which a large angle deflection resulted from a single collision between the alpha particle and the massive positive charge in the nucleus. This rivalry led to a bitter dispute between the two proponents (Wilson 1983). Rutherford's dilemma was that, on the one hand, he was entirely convinced and optimistic that his model of the atom provided a better explanation of experimental findings, and yet it seems that the prestige, authority, and even perhaps some reverence for his teacher (Thomson) made him waver in his conviction. A science student may wonder why Thomson and Rutherford did not meet over dinner (they were well know to each other) and decide in favor of one or the other model. These issues, if discussed in class and textbooks, could make the presentation of science much more human and motivating. Interestingly, none of the general chemistry textbooks (Niaz 1998) presented this historical episode, and two general physics textbooks (Rodríguez and Niaz 2004a) made a satisfactory presentation. One of these textbooks was by Cooper (1970), a Nobel Laureate in physics, who has endorsed a history and philosophy of science perspective in science textbooks (cf. Niaz et al. 2010b, for Cooper's perspective). In our efforts to study textbooks published in different cultures, next we analyzed 21 general chemistry textbooks published in Turkey and found that none of the textbooks referred to the Thomson-Rutherford controversy (cf. Niaz and Coştu 2009).

In a subsequent study, Rodríguez and Niaz (2002) reported that the importance of history of chemistry was recognized in the literature as early as the 1920s. O. Reinmuth (1932), editor of the *Journal of Chemical Education*, recognized the importance of the historical approach to teaching chemistry:

> It is much more important that he be shown how conclusions are reached on the basis of experimental evidence than that he memorize the conclusions. Too many students acquire the idea that scientific laws, theories and hypotheses spring full-armed from the brains of geniuses as the result of some occult phenomenon which the average man never experiences. (p. 1140)

Interestingly, this comes quite close and antecedes by about 30 years Schwab's (1962) advice that science cannot be taught as "rhetoric of conclusions." Indeed, Brush (1989) has cautioned that the historical approach does not consist in merely "assertion of the conclusions" that scientists have reached in the past, but rather "… to show how they were reached and what alternatives were plausibly advocated …." In order to pursue further the results reported by Niaz (1998) with respect to atomic models in general chemistry textbooks, Rodríguez and Niaz (2002) evaluated 30 textbooks published in the USA, in the period 1929–1967. Once again, results obtained revealed that most of the textbooks published in this period ignored the history and philosophy of science and lacked an understanding of the fact that students do not need to memorize experimental details but rather understand what the scientist was trying to do. It seems that despite the rhetoric with respect to the importance of history of chemistry, general chemistry textbooks have not changed much with respect to atomic models over 60 years (1929–1992).

A historical reconstruction of the determination of the elementary electrical charge and the ensuing controversy between R. Millikan and F. Ehrenhaft has been reported by Niaz (2000a). Both Millikan and Ehrenhaft had very similar experimental data, and still Millikan postulated the existence of a universal charged particle (electron) and Ehrenhaft postulated fractional charges (sub-electrons). Holton (1978) has provided the following insight on the impasse:

> It appeared that the same observational record could be used to demonstrate the *plausibility of two diametrically opposite theories*, held with great conviction by two well-equipped proponents and their respective collaborators. Initially, there was not even the convincing testimony of independent researchers. (pp. 199–200, emphasis added)

Niaz (2000a) has reported that of the 31 general chemistry textbooks analyzed (published in the USA, 1968–1999), none mentioned the Millikan-Ehrenhaft controversy. Similarly, none of the 43 general physics textbooks (published in the USA, 1970–2001) analyzed by Rodríguez and Niaz (2004b) mentioned the controversy. At this stage it could be argued that only advanced textbooks can be expected to include controversial aspects of scientific progress. To follow up on this, Niaz and Rodríguez (2005) analyzed 28 physical chemistry textbooks (published 1951–2002) and once again found that none mentioned the controversy. Interestingly, all these textbooks not only ignore the controversy but also consider the experiment to be characterized by its simplicity and precise results. For students, who still perform this experiment in their labs, such textbook presentations are quite perplexing (cf. Klassen 2009). Some textbooks even state that Millikan found no fractional charges and that the oil drop experiment was characterized by its simplicity and precise results. This in our opinion comes quite close to "distortion" of the historical events. Indeed, according to Kragh (1992) textbooks, "… not only distort historical reality, but they do so in a systematic way" (p. 359). Holton (2000) has endorsed the inclusion of such controversies in introductory science courses: "… introduction of the history and methodology of physics into the physics classroom, not least in terms of important controversies – is completely congenial to me … I agree one should teach research methodology in introductory physics and Millikan's case is certainly a well documented case that would lend itself to this purpose" (p. 1).

Padilla and Furio-Mas (2008) based on a historical reconstruction have traced the origin of concepts such as "chemical equivalent," "mole," and the "amount of substance." During the nineteenth century there was a widespread tendency (led by W. Ostwald) to replace the theoretical concept of "atom" with measurable notions of "volume" and "chemical equivalents," which led to considerable controversy. The progressive acceptance of the atomic-molecular theory was the origin of the magnitude, "amount of substance," and its unit, the "mole." These authors analyzed 30 general chemistry textbooks (published in the USA, 1980–2004) and found that a majority of the textbooks present the following: (a) amount of substance and mole within an ahistoric and unproblematic perspective and (b) misconceptions with respect to the mole concept, which is confused with number of elementary entities. It is concluded that lack of a historical perspective leads to distorted views of science, which does not facilitate meaningful learning. In an earlier study, Furió et al. (2000) analyzed 87 high school chemistry textbooks (published in Spain, 1976–1996), in order to determine the difficulties in teaching the concepts of “amount of substance” and “mole.” It was observed that a majority of the textbooks do not introduce these concepts in a meaningful way within a historical perspective.

The degree to which high school and university level general chemistry textbooks distort the image of science, while presenting acid–base reactions, is the subject of a study by Furió-Más et al. (2005). In order to understand acids and bases, these authors identified three historical models: macroscopic, Arrhenius, and Brönsted-Lowry. Authors have argued cogently with respect to understanding the macroscopic model based on early empirical knowledge of electrical conductivity of ionic solutions, before the later models. The study is based on 19 high school textbooks published (1975–2001) in Spain and 18 general chemistry textbooks published (1968–2000) in the USA. Results based on inter-rater agreements revealed the following: (a) Arrhenius and Brönsted-Lowry theories are described in all textbooks; however only 60 % justify the change from one theory to another; (b) 66 % of the textbooks ignored that the concept of hydrolysis helps to understand the conjugate acid–base pair in the Brönsted-Lowry theory; and (c) most textbooks presented a socially “neutral” description based on inductive generalizations that lead to a linear accumulative perspective of progress in science. It is plausible to suggest that the inclusion of the concept of acids and bases by G. N. Lewis would have provided a better historical perspective.

In the late nineteenth century, there was a dispute as to whether a mathematical description of osmotic pressure could contribute any chemical information with respect to what was happening at the molecular level during osmosis. This was particularly significant as the van’t Hoff osmotic pressure law, $\pi V = nRT$, was mathematically analogous to the ideal gas law, $PV = nRT$. By the middle of the twentieth century, based on thermodynamic concepts of osmosis, mathematical models provided greater chemical understanding of osmosis. However, by the end of the twentieth century, some chemists preferred a kinetic-molecular approach to osmosis rather than the thermodynamic approach. In order to understand these historical disputes, de Berg (2006) has analyzed 11 physical chemistry textbooks published in the period 1963–2002 (the USA = 7, UK = 4). Results obtained revealed the following: (a) A majority of the textbooks referred to and discussed the analogy between the van’t Hoff law and the ideal gas law; (b) except one, all textbooks provided a mathematical derivation of the van’t Hoff law; and (c) none of the textbooks referred to kinetic-molecular ideas. The author concluded that the kinetic-molecular approach is more accessible to students than the mathematical thermodynamic approach and thus deserves more attention in chemistry education, in order to facilitate greater understanding. Furthermore, thermodynamics should not just be a matter of manipulating symbols, but rather it is important to provide students with a qualitative sense of the problem.

Heat (an extensive property) and temperature (an intensive property) are an important part of the science curriculum at both the high school and university freshman level, and most students have considerable difficulty in differentiating between the two. An underlying issue that makes understanding difficult is the conceptual rivalry in the history of science between the caloric (heat as a substance) and the kinetic theories. According to Brush (1976), “The kinetic theory could not flourish until heat as a substance had been replaced by heat as atomic motion” (p. 8). De Berg (2008a) has analyzed the concepts of heat and temperature in 10 general chemistry textbooks published (1993–2006) in the USA. Results obtained revealed that heat is considered to be as follows: (a) *energy that flows* from an object at the higher temperature to one at the lower temperature; (b) *energy that is transferred* from an object at the higher temperature to one at a lower temperature; (c) process of energy transfer from a higher temperature object to a lower temperature object; (d) only three textbooks illustrated the difference between heat and temperature; and (e) no uniform picture of “heat” is presented and almost no exposure is given to the caloric theory. The author concluded that terms such as *heat flow* or *energy flow* are remnants of the caloric theory of heat and the language used: “…even in current textbooks is reminiscent of the old caloric theory…” (p. 86).

Chemistry students are generally not exposed to different ways of understanding a chemical reaction. De Berg (2008b) has analyzed eight chemistry textbooks published between 1758 and 1891 in order to understand the chemistry of the oxides of tin. This period is significant in chemical history as it covers the two chemical revolutions, associated with A. Lavoisier (1770–1790) and J. Dalton (1855–1875). Selected textbooks were from the UK, European continent, and the USA. Unlike the textbooks of today, these fulfilled multiple functions such as the teaching of chemistry to secondary, college, medicine, and pharmacy students. Results obtained provided insight into the foundation of a number of chemical ideas such as nomenclature and composition used in modern chemistry. Furthermore, four major preparation techniques for the production of tin oxides emerged: the heating of tin in air, the addition of nitric acid to tin, the alkaline hydrolysis of tin (II) and tin (IV) salts, and the hydrolysis of alkaline stannate salts. Early textbooks of the period give lengthy descriptions and explanations for these reaction schemes. It would be interesting to study this and similar topics in current textbooks.

In the early nineteenth century, Dalton’s research program in order to be operationalized required the following items as part of the positive heuristic (cf. Lakatos 1970): (a) chemical formulae, (b) atomic weights (masses), and (c) composition by weight of the compound. Early in Dalton’s career, only the third item was known and hence the inductivist approach concluded that only combining “equivalents” or “measures based on volumes” were important. The law of definite proportions in chemistry is basically an elaboration of the third item of Dalton’s positive heuristic. In contrast, Gay-Lussac’s law of combining volumes provided the antiatomists a rationale for accepting the laws of definite and multiple proportions without the “superfluous” atomic theory of Dalton. Niaz (2001a) analyzed 27 general chemistry textbooks (published in the USA, 1969–1999) to determine if they followed one of the following interpretations: (a) *Inductivist*: Gay-Lussac’s law of combining volumes provided a rationale for accepting the laws of definite and multiple proportions. (b) *Lakatosian*: Dalton’s atomic theory predicted and explained Gay-Lussac’s law of combining volumes. Results obtained (based on inter-rater agreements) revealed that only two textbooks followed the inductivist interpretation and the remaining 25 textbooks simply ignored the historical perspective.

The periodic table of chemical elements is considered to be a conceptual tool that helps to organize a great deal of information, leading to a better understanding of chemistry. Despite this overall positive picture, most chemistry teachers and textbooks give the impression that for almost 100 years (1820–1920), scientists had no idea or never asked the question as to whether there could be an underlying pattern to explain periodic properties of the elements. Brito et al. (2005) have presented a historical reconstruction of the development of the periodic table. The basic idea behind this study was the hypothesis that even before the electronic structure of the atom (Thomson, Lewis, Bohr, Moseley, and others) was discovered, different explanations were offered for periodicity. It is important to note that when D. Mendeleev (and others) started working on the periodic table, he had the following sources of information: Dalton's atomic theory, law of multiple proportions, Cannizaro's Karlsruhe lecture, fairly reliable atomic weights, atomicity (valence), and various physical and chemical properties of chemical elements. In his famous Faraday lecture, Mendeleev (1889) explained his hypothesis cogently: "… the veil which conceals the true conception of mass, it nevertheless indicated that the explanation of that conception must be searched for in the masses of atoms; the more so, *as all masses are nothing but aggregations, or additions, of chemical atoms …*" (p. 640, emphasis added). This clearly shows that among other factors, Mendeleev considered the atomic theory to be an important cause of periodicity of chemical elements. Based on inter-rater agreements, Brito and colleagues (2005) analyzed 57 general chemistry textbooks published (1968–2002) in the USA and found that a majority of the textbooks ignored the role played by the atomic theory in the development of the periodic table. It is concluded that it is more fruitful to present a more balanced picture to the students by highlighting how Mendeleev solved the dilemma by looking for underlying patterns to explain and understand periodicity.

The role of authors and publishers as agents of change in Spanish science pedagogical reform and textbooks has been explored by De Posada (1999). Fifty-eight high school chemistry textbooks published (1974–1998) in Spain were analyzed to understand the topic of metallic bonding. Results obtained revealed the following: (a) Almost half the textbooks simply define the metallic bond and thus obscure the relationship between models and experimental data; (b) theoretical models employed by textbooks are metaphorical in nature (similar to analogies) and are thus open to misinterpretations; (c) drawings used in textbooks need to be more explicit with respect to nature of metallic bonding; (d) the topic of metallic bonding needs to be integrated with other topics, in order to provide students meaningful learning; and (e) based on the General Act for the Educational System of 1990 (Spain), some textbooks had improved by including constructivist guidelines. This study could be extended by including the presentation of metallic bonding in university general chemistry textbooks.

In the early twentieth century, all chemical bonds were considered to be ionic (transfer of electrons), and even bonds in compounds such as methane and hydrogen were believed to be polar, despite their lack of polar properties. Lewis's (1916) theory of sharing electrons (covalent bond) when first proposed was completely out of tune with established belief. In order to understand the sharing of electrons, Lewis postulated the cubic atom (a theoretical device) that provided the rationale for the octet rule. For some chemists the idea of two sharing negative electrons was simply absurd and bizarre. Based on a historical reconstruction of the origin of the covalent bond, Niaz (2001b) has analyzed 27 general chemistry textbooks published (1968–1999) in the USA. Results obtained revealed (based on inter-rater agreements) that most textbooks did not deal adequately with the following aspects: (a) Postulation of the covalent bond by Lewis in 1916 posed considerable conceptual difficulties; (b) Lewis used the cubical atom in order to understand the sharing of electrons (octet rule); (c) sharing of electrons had to compete with the transfer of electrons (ionic bond), considered to be the dominant paradigm until about 1920; and (d) Pauli's exclusion principle (1925 and after) provides a theoretical explanation of the sharing of electrons, just as the cubical atom did previously. It is concluded that the transition from Lewis's cubic atom → Pauli's exclusion principle → what next provides an illustration of how scientific knowledge is tentative.

Shiland (1997) has analyzed eight high school chemistry textbooks published (1964–1994) in the USA, to evaluate the degree to which introduction of the quantum mechanical model of the atom complies with a conceptual change model (Posner et al. 1982). Four aspects of the model were operationalized by the following guidelines: (a) *Dissatisfaction* was measured by examining how the Bohr model was shown to be unsatisfactory and what specific evidence was provided; (b) *intelligibility*, which is the learner's ability to represent an idea, was measured by determining the number of pages required to present the theory; (c) *plausibility* was measured by examining whether the inadequacies of the Bohr model were addressed by the quantum model; and (d) *fruitfulness* was measured by listing problems or questions which required quantum theory to explain or predict an observable phenomena. Results obtained revealed that most textbooks did not fulfill the conditions required for conceptual change. It is concluded that high school chemistry teachers cannot rely on their textbooks to create the conditions necessary for conceptual change while introducing quantum mechanics.

Most students face considerable difficulty in understanding quantum mechanics and as a consequence use quantum numbers and electron configurations as algorithms that provide little insight in understanding progress in science. Cushing (1991) has referred to this as the level of empirical adequacy, namely, having a formula or algorithm that is capable of reproducing experimental data. Similarly, Posner and colleagues (1982) have outlined a series of criteria for promoting conceptual change that were used by Shiland (1997) to understand quantum mechanics in high school chemistry textbooks. Based on this conceptual framework, Niaz and Fernández (2008) have analyzed 55 general chemistry textbooks published (1968–2002) in the USA. Criteria based on the following aspects were elaborated to evaluate the textbooks: (a) origin of the quantum hypothesis, (b) alternative interpretations of quantum mechanics, (c) differentiation between an orbital and electron density, (d) differentiation and comparison between classical and quantum mechanics, and (e) introduction of quantum numbers based on electron density. Results obtained (based on inter-rater agreements) showed the following: (i) Most textbooks provide low dissatisfaction, intelligibility, plausibility, and fruitfulness on criteria a, b, and c;

(ii) on criterion d, some textbooks were partially intelligible (providing analogies) and partially plausible (providing thought-provoking ideas); and (iii) on criterion e, some textbooks were partially plausible (providing experimental data of ionization energies), and only one textbook fulfilled the conditions for fruitfulness by showing how heights of the peaks from photoelectron spectroscopy correspond to the number of electrons.

Teaching of chemistry at the college and university level in most parts of the world is oriented towards the preparation of chemists and other science-based professionals. *Chemistry in Context: Applying Chemistry to* Society, a textbook for non-science majors, has been developed by Schwartz and colleagues (1997) under the sponsorship of the *American Chemical Society*. Schwartz (1999) summarizes the origin, development, content, pedagogy, evaluation, and influence of this textbook and considers its potential implications for other disciplines and the instruction of science majors. The book introduces the principles of chemistry within the context of socially significant issues, such as global warming, ozone depletion, alternate energy sources, nutrition, and genetic engineering. The chemistry is included as needed to inform an understanding of chemical principles, and an additional feature is the inclusion of student-centered activities designed to promote critical thinking.

44.4 University and High School Physics Textbooks

According to Gardner (1999), although as science teachers we are generally not trained in history and philosophy of science, still “our implicit theories about the nature of science and technology influence the stories we tell our students” (p. 330). This clearly shows the need to take into consideration teachers’ prior epistemological beliefs. Indeed, this is an important guideline for both textbook authors and curriculum developers. This study discusses the meanings attached to the terms “science” and “technology” and outlines four views of the nature of their relationship: (a) *idealist view* (technology as applied science), (b) *demarcationist view* (separate fields), (c) *materialist view* (technology as a necessary precursor to science), and (d) *interactionist view* (scientists and technologists working together). Five high school physics textbooks published in Canada (1986–1992) were analyzed within this perspective. Results obtained revealed various positive features, such as recognition of the human face of science and technology, frequent reference to careers in which knowledge of physics might be useful, and many illustrations of interesting technological artifacts. However, some of the textbooks are dominated by an idealist storyline which represents a limited view.

Newtonian mechanics has been the subject of critical appraisal by E. Mach (1960/1883). Mach’s work was deeply rooted in his philosophy which assumed that only sensations can be known and are real, and he was particularly critical of Newtonian concepts of absolute time and space and inertial mass. Mach’s views with respect to matter and motion were later known as Mach’s principle, which was of heuristic value for Einstein’s development of his general theory of relativity.

Assis and Zylbersztajn (2001) have analyzed five general physics textbooks published (1963–1995) in the USA, in order to trace Mach's influence in the teaching of classical mechanics. Results obtained revealed that all five textbooks are influenced by Mach and especially with respect to the dynamical operational definition of inertial mass. Interestingly, however, none of the textbooks recognized that Mach was the originator of this definition of inertial mass.

Starting from Newton to Poincaré, the concept of force in physics has been the source of considerable discussion. At the International Congress for Philosophy in Paris in 1900, Poincaré asked if the fundamental equation of dynamics, $F = ma$, is verifiable experimentally. Later he himself responded by pointing that the problem was difficult as we do not even know what force and mass are. In order to scrutinize this difficulty, Coelho (2010) has analyzed about a hundred textbooks published in the twentieth and twenty-first centuries in different parts of the world. Knowing the difficulties involved some textbooks do not provide a definition of force. Most of the textbooks, however, define force to be the cause of acceleration. It is argued that as acceleration is observable, its cause must be something real. Thus, force is real. This interpretation has been questioned by some physicists and philosophers of science. According to Coelho (2010), "… the mere fact that these two kinds of theses coexist, shows the difficulty in 'seeing' force in phenomena" (p. 91).

Galili and Tseitlin (2003) have traced the historical origin of Newton's first law (NFL), which is the law of inertia, by consulting new translations of Newton's work in the twentieth century. This literature shows the richness of NFL in understanding the meaning of inertia. These authors analyzed 40 introductory physics textbook (high school, college, and university) published in Israel and the USA. Results obtained revealed that most textbooks (even those widely used) did not refer to NFL as it was considered to be a special case of Newton's second law. Finally, the authors concluded: "Newton's First Law is far from just a trivial special case of Newton's Second Law. As such, NFL can, and should, be carefully preserved and studied in the corpus of physics knowledge transmitted through the generations" (p. 68).

The presentation of the weight concept as a gravitational force has been questioned by Galili (2001). Even popular general physics textbooks (e.g., Sears & Zemansky) through many editions used worldwide have endorsed the following definition of weight as a gravitational force: "The weight of a body is the total gravitational force exerted on the body by all other bodies in the universe." According to Galili (2001), "This obscure definition, never introduced by Newton, can be neither empirically employed nor theoretically validated" (p. 1081). As an alternative based on a historical reconstruction, Galili has suggested an operational definition that distinguishes between weight and gravitational force in the following terms: "Weight of the body is the force, which acts downwards and causes spontaneous falling. Numerically, weight is given by the product mg^*, with g^* – the acceleration of a free fall, as it is measured in a particular frame of reference" (pp. 1082–1083). The study revealed that very few textbooks (e.g., Keller, Lerner) present this definition. Furthermore, given the complexity of the issues involved, some textbooks have simply excluded the definition of the weight concept.

The concept of electric field has been the subject of a study by Pocovi and Finley (2003), based on a historical reconstruction of the ideas of M. Faraday, J. C. Maxwell, and A. Einstein. Maxwell was able to give more impetus to Faraday's ideas of lines of force by expressing them mathematically. At this stage, for the action-at-a-distance theorists, forces were transmitted at a distance, whereas for the field theorists, the transmission took place through a medium. Einstein gave the field the status of a fundamental entity, so that any electromagnetic problem was completely described by the field equations. These authors analyzed two well-known and widely used general physics textbooks published (1978, 1991) in the USA. Results obtained revealed that both textbooks did not adequately explain the field concept in the description of electromagnetic phenomena. Furthermore, the equivalence of the action-at-a-distance and field views within electrostatics was generally ignored. According to the authors such presentations are problematic, as textbooks are assumed to be accurate, complete, coherent, and the primary source of information for students.

The development of the concept and theories of magnetic field within a historical perspective has been explored by Guisasola et al. (2005). These authors analyzed 30 introductory physics and electromagnetism textbooks published (1972–1999) in the USA. Results obtained (based on inter-rater agreements) revealed that a majority of the textbooks (a) present the introduction to the theory of magnetic field in a nonproblematic, nonhistorical, and linear accumulative manner. Development of the theory of the magnetic field had to overcome many difficulties, and various theories were proposed; (b) ignore the problems which occurred in identifying the sources of stationary magnetic field and the equivalence between charges in movement and magnets; (c) do not relate the theory of magnetic field to theories from other areas of physics, such as mechanics or optics; (d) do not discuss Maxwell's laws as an attempt to unify characteristics common to electricity and magnetism; and (e) possible limitations of the theory are not discussed.

Vaquero and Santos (2001) have analyzed 38 high school and general physics textbooks published (1844–1900) in Spain in order to explore the role played by heat and kinetic theory. Authors used the following questions for evaluating the textbooks: (1) use of imponderable fluids (18 textbooks were classified as affirmative), (2) use of the term caloric to refer to heat (14 textbooks were classified as affirmative), (3) use of the concept of energy in a general form (14 textbooks were classified as affirmative), (4) use of the mechanical theory of heat (21 textbooks were classified as affirmative), and (5) use of the kinetic theory of gases (5 textbooks were classified as affirmative). According to the authors affirmative responses to the first two questions would indicate traditionalism and to questions 3 and 4, modernity. If the kinetic theory of gases appeared, then the textbooks were considered as "quite complete." This state of the textbooks is attributed to the curricular plans of Spanish universities and the overall political climate in which physics was relegated to a minor faculty. It is interesting to note that even current chemistry textbooks published in the USA (as reported by De Berg 2008a, see previous section) and physics textbooks (cf. Cotignola et al. 2002) have difficulties in the presentation of heat. Similarly, the presentation of kinetic theory in current textbooks (published in the USA, cf. Niaz 2000b) lacks the historical context in which the kinetic theory developed. Further analyses of textbooks published in Spain after 1900 could provide evidence as to how kinetic theory was introduced progressively.

An analysis of thermodynamics in general physics textbooks has led Tarsitani and Vicentini (1996) to suggest that "… several mental representations of the same subject do exist, even in the case of a 'mature' science, and in fact are often found in scientific literature … different textbooks may expound the same subject agreeing on many phenomenological and theoretical aspects, yet disagreeing not only on the logical structure and definition of fundamental concepts, but also on the general view of the scope and object of the subject matter" (p. 51). Based on a historical reconstruction, these authors have found two approaches to presenting thermodynamics in textbooks: (a) statistical approach (following among sources, J. C. Maxwell's *theory of heat*) and (b) phenomenological approach (following primarily M. Planck's *Treatise on Thermodynamics*). Two examples of textbooks (published in the UK & USA) that follow the statistical approach are discussed. Three examples of textbooks (two published in the USA and one in Switzerland) that follow the phenomenological approach are presented. A comparison of the two types of textbooks shows that in the phenomenological approach, physical theory is nearest to experience and the kinetic theory does not play a central role. On the other hand, the statistical approach has its own problems, as it works with abstract models, which makes the explanation of the second law and entropy problematic.

Niss (2009) has emphasized the importance of metamodeling in statistical mechanics textbooks, as it facilitates a better understanding of the purpose of modeling and hence the nature of science. Textbooks were selected according to the following criteria: inclusion of a chapter on phase transitions, articulate modeling issues, represent a class of textbooks, and not too idiosyncratic in approach. Five textbooks were selected, considered to be classics in the field, and published (UK = 1; USA = 4), over a period of 70 years (1936–2001). Results obtained revealed the following: (a) Different messages are sent with respect to what constitutes a good model; (b) models are used to elaborate phenomenological theories of phase transitions; however these theories differ widely; (c) present different notions of what it means to understand a physical phenomenon; and (d) recent textbooks pay more attention to universality that is capturing different physical systems under the same umbrella. It was concluded that the five textbooks provide different metamodeling knowledge, which is not presented explicitly.

Cotignola et al. (2002) have analyzed thermodynamic concepts in seven general physics textbooks published in the USA (1991–1998). According to the authors, "Most books now use a definition of heat closer to the presently accepted one: a process of energy transfer associated with a temperature difference between the system under study and its surroundings. In spite of a correct initial definition, many authors (Resnick, Tipler, Giancoli, Serway and Hewitt) finally succumb to 'heat is a form of energy'" (p. 285). Joule's experiments referred to the different equivalent processes capable of producing the same increase in the system's temperature. Given the central role heat had in the beginnings of thermodynamics, five of the textbooks while describing Joule's experiments do not correctly differentiate between heat and energy. Only three of the textbooks correctly explain internal energy, namely, energy associated with the internal structure of the system under study.

It is well known that Thomas Kuhn directed the project "Sources for History of Quantum Physics," a valuable archive now available at various institutions around the world. Based on this experience, Kuhn raised a provocative question: Who first proposed the quantum hypothesis? Kuhn (1978) stated categorically:

> … the arguments in Planck's first quantum papers [Planck 1990] did not, as I now read them, seem to place any restrictions on the energy of the hypothetical resonators that their author had introduced to equilibrate the distribution of energy in the black-body radiation field. Planck's resonators, I concluded, absorbed and emitted energy continuously at a rate governed precisely by Maxwell's equations. His theory was still classical …. (p. viii)

Kuhn concluded that it was P. Ehrenfest and A. Einstein who first recognized that the blackbody law could not be derived without restricting resonator energy to integral multiples of hν. In other words, Planck in 1900 simply introduced an approximate mathematical quantization in doing the calculations. Kuhn's thesis has been endorsed by some historians (e.g., Brush 2000; Kragh 1999). However, physicists have in general resented the attempt to deprive Planck of credit for the quantum hypothesis. In order to evaluate the support for Kuhn's thesis, Brush (2000) has analyzed 28 general physics textbooks published in the USA (1990–1997). Results obtained showed that only six textbooks supported Kuhn's hypothesis with respect to the origin of the quantum hypothesis. In comparison, Niaz and Fernández (2008) found that of the 55 general chemistry textbooks published in the USA, only one reluctantly supported Kuhn's hypothesis.

Tampakis and Skordoulis (2007) have examined the reception of quantum mechanics in the Greek scientific community through nine physics textbooks published in Greece (1913–1963). Authors found that the quantum theory appeared first in a textbook in 1925, with a brief mention of Planck's hypothesis and the photoelectric effect. It was not until 1962 that quantum mechanics was finally established in Greek textbooks. Authors attribute this delayed appearance to three factors: scientific, social, and ideological. It is concluded that the debate between the political left and right and the church organizations led to an extremely idealistic misinterpretation of the theory, before a more technical interpretation appeared in the textbooks.

Thought experiments (TEs) have played an important role in the history of science and have also been recognized in science education (Gilbert and Reiner 2000). Velentzas et al. (2007) have investigated the role of thought experiments in the theory of relativity and quantum mechanics in general physics textbooks (ten published in the USA, 1961–1997, and one in Greece, 1999). In general, these textbooks considered TEs to be an important tool when presenting these topics, and the following were used quite frequently: Einstein's train and elevator and Heisenberg's microscope. Despite the use of TEs, some textbooks preferred real experiments, especially the Michelson-Morley (MM) experiment in the context of the theory of relativity. Indeed, the MM experiment shows how in the history of science experiments are difficult to understand and interpret. According to Lakatos (1970, p. 162), starting from 1905, it took almost 25 years for the MM to be understood and considered as the "greatest negative experiment in the history of science." Brush (2000) has analyzed 26 general physics textbooks published in the USA (1990–1997), with respect to the "genetic" relationship between MM and Einstein's special theory of relativity (STR). Results obtained revealed that nine textbooks still attributed Einstein's theory to the negative result of the MM. Nevertheless, it is a cause of concern that these nine textbooks included those widely used all over the world (e.g., Serway, Sears, Zemansky). More recently, Arriassecq and Greca (2007) have analyzed the MM experiment in high school physics textbooks published in Argentina (n = 9, 1980–2000) and general physics textbooks published in the USA (n = 6, 1971–2001). Most textbooks in their study suggested that the starting point for Einstein's STR was the MM experiment, which contributes to generate a distorted view of the dynamics of scientific research. Even textbooks written by famous physicists (e.g., *Feynman's Lectures on Physics*) contribute to this empiricist perspective of science. The genetic relationship between the Michelson-Morley experiment and Einstein's STR in physics textbooks published in three different countries (Argentina, Greece, USA) is a good example of what Holton (1969) has referred to as the myth of experimenticism. According to this myth, progress in science is presented as the inexorable result of logically sound conclusions derived from experimentally indubitable premises.

Treagust and Harrison (2000) have analyzed Feynman's (1994) Lecture 1 "atoms in motion" in his *Six Easy Pieces* and consider it to be "a classic example of expert pedagogical content knowing" (p. 1162). The *Lecture* was found to contain effective explanations based on science content, educational context, and teacher- and student-related factors. Furthermore, these authors differentiate between scientists' explanations and science teaching explanations. Science explanations are characterized as strictly theory and evidence driven. In contrast, the *Lecture* includes rich and creative metaphors, analogies, and models based on anthropomorphisms and teleological expressions.

Millikan's (1916) determination of Planck's constant h (photoelectric effect) has been the subject of a study by Niaz et al. (2010a). Of the 103 general physics textbooks (published in the USA, between 1950s and 2000s) analyzed, only five made a brief mention of Millikan's presupposition and belief in the classical wave theory of light. A historical reconstruction shows that Millikan recognized the validity of Einstein's photoelectric equation and at the same time questioned the underlying hypothesis of light quanta. Very few textbooks mentioned that Millikan's experimental data provided support for Einstein equation but not his theory. Again, none of the textbooks mentioned that scientific theories are underdetermined by experimental evidence. Only one of the textbooks came close to referring to the dilemma faced with respect to the lack of acceptance of Einstein's quantum hypothesis in the scientific community, precisely because of the rivalry with the classical wave theory of light.

44.5 School Science Textbooks

Leite (2002) has analyzed five high school physics textbooks published (1996–1998) in Portugal based on criteria, such as historical experiments, analyses of data from historical experiments, integration of historical references within the text, use of original historical sources, evolution of science, and sociopolitical context in scientific research, among others. Results obtained (based on inter-rater agreement) led the author to conclude that the historical content included in these textbooks hardly provided students with an adequate image of science and the work of the scientists.

Milne (1998) has emphasized the role of stories in science textbooks as presentation of science cannot be reduced to just including facts. Stories can take various forms: (a) Heroic: focus on a hero who single-handedly contributed to the development of science. (b) Discovery: scientific knowledge is presented as having occurred as the result of an accident. (c) Declarative: processes or scientific concepts as objects that are open to observation by anyone. (d) Politically correct: a critical examination of the interaction between science and society. Examples from high school textbooks are provided to illustrate heroic stories, such as Galileo as an individual who had the courage to stand against the dark forces of the inquisition. Milne (1998) concluded: "… if we wish to involve students more in thinking about the enterprise that we call science, we would do well to tell stories that emphasize the human aspects of the development of scientific knowledge" (p. 186). Milne also presented her own version of the life and work of Galileo. This version has been critiqued by Whitaker (1999), as it lacked some historical details and the necessary differentiation between "observations" and "experimentation." The role of experimentation in Galileo's work is the subject of considerable debate. Milne (1999) responded by pointing out that her story did not represent the truth and that there are various ways to elaborate stories in science.

The role of ideologies in Norwegian grade 8 science textbooks (n = 4, published in 1997) has been explored by Knain (2001). Ideologies are considered to be grounded in worldviews (Cobern 1996) which are culturally influenced and shared by people through social interaction. For each textbook, 30 pages were selected from the following topics: nature of science (introductory chapter), nature (astronomy), and society (fighting diseases). For example, portraying scientific development as dependent on the work of individual scientists doing crucial experiments is evident from the following historical note in one of the textbooks: "An Englishman, Alexander Fleming, discovered that a certain mould fungus with the name *Penicillin* precipitates a substance that kills bacteria" (p. 325). For most textbooks in this study, experiments and observations are what make science different from other ways of knowing. Furthermore, controversies constitute an important part of science as experimental results are difficult to interpret and their relevance in the sociopolitical context is not obvious.

Importance of biographies of scientists in science education has been explored by Dagher and Ford (2005). Authors analyzed the images of science and scientists in 12 biographies of historic and contemporary scientists written for primary and middle school children, published in the USA (1987–2003), and addressed the following research questions: (1) How is the scientist described in the biography? (2) What is the nature and process of scientific knowledge? (3) How are social processes related to science portrayed? Results obtained revealed a marked difference in how different authors portrayed their subject depending on the age of the target audience. Biographies for primary school (e.g., M. Curie & A. Einstein) emphasize personal characteristics and childhood of the scientists. Biographies for secondary school provide more details of nature of scientific work and processes of science. Authors concluded that biographies can be used: "… to provide useful springboards for arousing student curiosity and interest in exploring the historical record" (p. 391).

As a topic of the science curriculum, teaching of the pendulum incorporates conceptual, methodological, and cultural aspects (Matthews et al. 2005). Based on these aspects Koliopoulos and Constantino (2005) have analyzed school science textbooks (primary and secondary) published in Greece and Cyprus. Results obtained revealed that in both countries the pendulum is confined mainly to the study of the simple pendulum, which is incidental and limited and never introduced as a comprehensive unit. At the gymnasium level the textbooks espouse an empirical approach in which the dependence of the period on the length of the string of the simple pendulum and the acceleration of gravity emerge from a simple observation of the pendulum motion. At the lyceum level apart from the experimental activity, textbooks include the derivation of mathematical relations. Given the pendulum's historical connection with clock making, time measurement, the longitude problem, and navigation, it readily constitutes "…a window on the scientific revolution" (Matthews 2000, p. 293). Despite this rich cultural context, we found only one study dealing with the presentation of the pendulum in textbooks.

44.6 Educational Implications

Various topics of the science curriculum provide an opportunity to illustrate the tentative nature of scientific knowledge, and still very few textbooks referred to this important aspect of nature of science. American Association for the Advancement of Science has expressed this in cogent terms: "The notion that scientific knowledge is always subject to modification can be difficult for students to grasp. It seems to oppose the certainty and truth popularly accorded to science, and runs counter to the yearning for certainty that is characteristic of most cultures, perhaps especially so among youth" (AAAS 1993, p. 5). Indeed, divergent opinions that often lead to controversies are one of the most important aspects of scientific progress (Niaz 2009a). Modern philosophers of science have referred to this facet of nature of science in explicit terms:

> Many major steps in science, probably all dramatic changes, and most of the fundamental achievements of what we now take as the advancement or progress of scientific knowledge have been controversial and have involved some dispute or another. Scientific controversies are found throughout the history of science. This is so well known that it is trivial. What is not so obvious and deserves attention is a sort of paradoxical dissociation between science as actually practiced and science as perceived or depicted by both scientists and philosophers. While nobody would deny that science in the making has been replete with controversies, the same people often depict its essence or end product as free from disputes, as the uncontroversial rational human endeavor par excellence. (Machamer et al. 2000, p. 3)

Similarly, Dybowski (2001), a practicing teacher, has designed an innovative course in the history of physical chemistry that facilitates an appreciation of how scientific inquiry actually happens in research laboratories and recounted his experience: "… we sometimes find that we come away with two (or more) differing views of events that cannot be reconciled. At first, this failure to bring closure is disconcerting to some students, but one underlying theme of the course is the appreciation of the *possibility of divergent opinions on certain issues, even in a science like chemistry*" (p. 1623, emphasis added). Different approaches to teaching thermodynamics (cf. Tarsitani and Vicentini 1996, physics section) are illustrative of this dilemma.

Most textbooks in this review presented the experimental details, without the conceptualization that progress in science is based on competing frameworks of understanding that clash in the face of evidence. Writing in a special issue dedicated to *Nature of Science in Science Education*, Lederman et al. (1998) asked a very pertinent question, "*what seems to be the problem?"* and then responded:

> Most texts briefly, and inadequately, discuss the nature of science in the opening chapter, and then portray science in a distorted, positivistic, and 'final form' fashion throughout the rest of the book. (p. 507)

Despite some improvement, it seems that problems with respect to most textbooks seem to be the same. In this context, Kubli (2005) has emphasized the role of "real" experiments: "The element of uncertainty – the sure sign of a *real experiment* – is drastically reduced if we repeat an experiment whose result can be deduced from the textbook. But even in the classroom, we can regenerate something of the pioneering spirit if we show how difficult it originally was to arrive at a result, and if we can convey the fascination of breaking new ground" (pp. 515–516, italics added). Based on wave-particle duality, Niaz and Marcano (2012) have provided further evidence on this aspect.

Almost half a century ago, Polanyi (1964) had drawn our attention to an important facet of textbooks, by emphasizing the degree to which established knowledge in textbooks departs from the events associated with the original discovery:

> Yet as we pursue scientific discoveries through their consecutive publication on their way to the textbooks, which eventually assures their reception as part of established knowledge by successive generations of students, and through these by the general public, we observe that the intellectual passions aroused by them appear gradually toned down to a faint echo of their discoverer's first excitement at the moment of Illumination … A transition takes place here from a heuristic act to the routine teaching and learning of its results, and eventually to the mere holding of these as known and true, in the course of which the personal participation of the knower is altogether transformed. (pp. 171–172)

Drawing on the "events associated with the original discovery," "excitement at the moment of illumination," and teaching science as practiced by scientists can indeed be an important guideline for future science textbooks (Niaz 2010b).

44.7 Conclusion

This chapter analyzed 52 studies published over a period of 15 years (1969–2010) in four major science education journals, and the following are some of the important findings:

(a) Most biology, chemistry, physics, and school science textbooks lack a historical perspective required to facilitate a better understanding of the dynamics of scientific progress.

(b) Most of the textbooks analyzed were published in the USA and to a much lesser extent from the following countries: Argentina, Australia, Brazil, Canada, Cyprus, Greece, Israel, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, and the UK.

(c) Few studies provided details of the procedure and reliability of the application of the criteria/rubric for analyzing textbooks. One study (Chiappetta and Fillman 2007) used Cohen's *kappa* statistic, and some studies provided details of inter-rater agreements.

(d) Studies analyzed in this chapter refer to a wide range of 21 subjects that form part of the science curriculum, such as the following: nature of science = 9, atomic structure = 8, Newtonian mechanics = 5, quantum mechanics = 4, special theory of relativity (Michelson-Morley experiment) = 4, evolution = 4, gene concept = 1, oil drop experiment = 2, heat and temperature = 2, chemical bonding = 2, electromagnetism = 2, thermodynamics = 2, science stories = 2, laboratory manuals (biology) = 1, acids and bases = 1, osmotic pressure = 1, periodic table = 1, kinetic theory = 1, statistical mechanics = 1, photoelectric effect = 1, and pendulum = 1 (note this gives a total of 56 instead of 52, as some studies dealt with more than one subject). In all these studies, a majority of the textbooks lacked a history and philosophy of science (HPS) perspective. However, it is important to note that a small number of textbooks did provide material based on HPS that can further students' understanding of science. This shows that HPS is already "inside" the science curriculum, provided textbook authors and teachers make an effort to scrutinize the historical record.

(e) Review of the literature in this chapter revealed that if a topic/concept was difficult/controversial, textbooks try to avoid presenting it, and the following are some of the examples: (i) concept of force (Coelho 2010), (ii) concept of weight (Galili 2001), (iii) Newton's first law (Galili and Tseitlin 2003), (iv) inclusion of evolution which can facilitate "removal of prejudices" (Barberá et al. 1999; Skoog 2005), (v) difference between heat and temperature (Cotignola et al. 2002; de Berg 2008a), (vi) different approaches to thermodynamics (Tarsitani and Vicentini 1996), (vii) role of atomic theory in the development of the periodic table (Brito et al. 2005), (viii) postulation of the sharing of electrons, covalent bond (Niaz 2001b), (ix) origin of the quantum hypothesis (Brush 2000; Niaz and Fernández 2008), (x) special theory of relativity and the Michelson-Morley experiment (Brush 2000; Arriassecq and Greca 2007), (xi) interpretation of alpha particle experiments by Thomson and Rutherford (Niaz 1998), (xii) interpretation of oil drop experiment by Millikan and Ehrenhaft (Holton 1978; Niaz 2000a), and (xiii) photoelectric effect. Millikan's data supported Einstein's equation but not his theory (Niaz et al. 2010a).

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Chapter 45
Revisiting School Scientific Argumentation from the Perspective of the History and Philosophy of Science

Agustín Adúriz-Bravo

45.1 Argumentation in Science and in Science Education

The purpose of this chapter is to examine the notion of scientific argumentation as it is applied in the realm of science education nowadays, but this examination is done – in accordance with the thematic thread of this handbook – shifting from the extensively used discursive perspective to one centred on *metatheoretical* issues. In order to set an initial consensus for the discussion that follows, it might be convenient to advance here a broad definition of argumentation, which will be eventually revisited to incorporate more theoretical elements. Using the phrasing on the back cover of Myint Swe Khine's (2012, n/p) compilation, scientific argumentation could be loosely identified with 'arriving at conclusions on a topic through a process of logical reasoning that includes debate and persuasion'. This definition points out that an argument typically involves (a) supporting an assertion on other elements, (b) a range of options when choosing such elements and (c) strategies to convince the argument's recipients that the favoured option is appropriate.

Literature reviews around argumentative practices in the science classroom rapidly conduct to acknowledging that argumentation is a central issue or focus – or more properly a 'line of research' (Jiménez-Aleixandre and Erduran 2008) or a 'strand' (Nielsen 2011) – within current didactics of science (i.e. science education as an academic discipline). However, such reviews show, at the same time, that 'argumentation in the field of science education has constituted itself into a multi-disciplinary topic, most profoundly approached from language sciences' (Archila 2012, p. 363;

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my translation). Hence, the interest of this chapter to recover an *epistemic* focus, which could be broadly defined, borrowing Greg Kelly and Charles Bazerman's words, as the recognition

> that writing and argument play important roles in scientists' and technologists' thinking and forming knowledge communities […]. The forms of expression, invention, and knowledge are responsive to the particular argumentative fields of the professions and disciplines. The epistemic activity of researchers is shaped by rhetorical concerns of who is to be convinced of what, how others respond to novel work, what the organization of their communicative activity is, and what the goals of community cooperation are […]. The representation and role of evidence in relation to generalizations and claims has been a particularly crucial matter in the development of scientific argument. (Kelly and Bazerman 2003, pp. 28–29)

Indeed, argumentation has been recognised by some traditions, authors and texts in the philosophy of science as a key epistemic feature of the scientific enterprise,[1] i.e. a feature constitutive of its very nature, which serves to *demarcate* science from other human activities. It could arguably be stated that

> the majority of philosophical conceptions on the structure of a scientific theory, as well as some of the most important models of [scientific] explanation, incorporate argumentation (understood as justifying inferences) as a central piece in the scientific machinery. (Asti Vera and Ambrosini 2010, p. 6; my translation)

This argumentation-based perspective on the nature of science is apparent in Stephen Toulmin's (1958) famous book, *The uses of argument*, especially in essay IV, where he examines 'substantial arguments' in the experimental sciences. But it should be noted that although argumentation-like processes have been consistently considered in the metatheoretical discussion of scientific processes and products by philosophers (e.g. Giere et al. 2005), the use of the expression 'scientific argumentation' is not as extended as it could be expected within the philosophy of science – at least until very recently. This may be partly due to the concealment of the more elaborate communicative aspects of science in the rather formalist, syntactic view 'received' from the Vienna Circle. In the philosophy of science, the idea of scientific argumentation has been very usually rephrased in terms of explanation, justification, debate, controversy, judgement, persuasion, rhetoric, etc.

Many portrayals of science-in-the-making have pointed to the existence of an extremely elaborate, social, use of *evidences* to give support to our complex, articulated understandings of the natural world (i.e. *scientific explanations*) and, at the same time, to *convince* other people that such understandings are plausible

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[1] See the following 'focussed' philosophy of science textbooks for more or less extensive discussions around philosophers that inspect the centrality of argumentation in science: Asti Vera and Ambrosini (2010), Føllesdal and Walløe (1986), and Salmon (1995). Also of particular interest for this chapter are the portrayals of the 'combined' scientific practice of argumentation-explanation that revolve around the notion of *abductive* reasoning (cf., Adúriz-Bravo 2005; Aliseda 2006; Bex and Walton 2012; Giere 1988; Giere et al. 2005; Lawson 2009; Samaja 1999).

and fruitful.[2] Such accounts of the nature of science share four main characteristics:

1. They consider explanation – in argumentative contexts – as one of the core epistemic practices of science (cf., Bricker and Bell 2008; Jiménez-Aleixandre and Erduran 2008; Khine 2012, who all cite the *philosophical* origins of this idea that has been imported into didactics of science).
2. They revolve around the notion of evidence (or data, proof, reasons, supporting assertions, warrant and a host of other phrasings) as a key to understand scientific semiosis (i.e. meaning production).
3. They highlight the constituent intentions of the 'acts of speech' (*à la* John Searle) or 'language games' (*à la* Ludwig Wittgenstein)[3] included in the very fabric of the scientific activity (cf., Asti Vera and Ambrosini 2010).
4. They acknowledge the social and situated character of the aforementioned processes, which are developed at the interior of specific knowledge communities with their rules and values.

In accordance with this pre-eminent role given to argumentation in science, it has been repeatedly suggested from didactics of science that argumentation should be incorporated as a major component in a high-quality science education for all (cf., Erduran and Jiménez-Aleixandre 2008; Jiménez-Aleixandre 2010; Osborne 2005). The consideration of argumentation as a central process of 'scientists' science' has permitted didacticians of science (i.e. science educators as researchers) to advance at least three main reasons for the inclusion of argumentation in 'school science'[4] (cf., von Aufschnaiter et al. 2008, p. 102):

1. Meaningful and critical science learning requires argumentation. In this sense, 'learning to argue is seen as a core process […] in learning to think and to construct new understandings [, since] comprehending why ideas are wrong matters as much as understanding why other ideas might be right' (Osborne 2010, p. 464). Thus, mastering the argumentative aspects of science and examining actual pieces of scientific argumentation would help distinguish claims and statements that are supported from those that are not, and also to assess the

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[2] Leema Kuhn Berland and Brian Reiser (2009) also present a three-element characterisation of argumentation, which is very similar to the one proposed here. They talk about: '(1) using evidence and general science concepts to *make sense of the specific phenomena being studied*; (2) *articulating these understandings*; and (3) *persuading others of these explanations* by using the ideas of science to explicitly connect the evidence to the knowledge claims' (p. 29; emphasis in the original).

[3] These two theoretical constructs refer to the communicative activity as a whole, with all its pragmatic constraints, where different types of texts – among them, arguments – are produced.

[4] The distinction here between 'scientists' science' and 'school science' (cf., Izquierdo-Aymerich and Adúriz-Bravo 2003) is based on the French tradition in *didactique des sciences*. In the theory of didactical transposition (Chevallard 1991), there is a 'savoir savant' constructed within the disciplines and a 'savoir enseigné', taught at school, which emerges from transposing (i.e. performing adaptive operations on) the former. Thus, science as done at school resembles in some aspects, and differs in some others from, science as performed by scientists.

quality and pertinence of the supports provided. It could be safely stated that this first reason is very general, goes beyond scientific argumentation and its epistemology and values arguing in all its cognitive, metacognitive and communicative dimensions,[5] linked to 'fostering the development of students' rationality' (Siegel 1995, p. 159).

2. Since scientists produce and evaluate arguments all the time in order to do science, a school science that is structured around argumentation would convey important messages about the nature of science, hence the need to inform argumentation-based instruction with findings from the philosophy and history of science. In coherence with this second reason, in science classes, a non-negligible part of students' activity would be to construct arguments around their understandings of the natural world, and to share, defend and criticise such arguments as it is done in actual scientific practice (cf., Driver et al. 2000, for school science, and Giere 1988, for scientists' science). Here we could use the distinction proposed by Marilar Jiménez-Aleixandre and colleagues (2000) between doing authentic school science and 'doing the lesson', the first one being characterised by 'the generation and justification of knowledge claims, beliefs, and actions taken to understand nature' (p. 758). It should be noted, of course, that the resulting nature of science that would circulate in the classroom *would heavily depend on the notion of argumentation that is being implemented*, be it more 'rationalist' or more 'constructivist' (see the 'tensions' defined in Sect. 45.2).
3. When considering science education as a tool for scientific literacy and citizen education, it is suggested that students need to engage in argumentation in order to tackle decision-making and to participate in socioscientific debates similar to those that they will encounter in their adult lives. As Jiménez-Aleixandre and colleagues (2000) point out: one of the most currently valued educational goals is 'equip[ping] students with capacities for reasoning about problems and issues, be they practical, pragmatic, moral and/or theoretical' (p. 757); it has been repeatedly proposed that argumentation would foster such capacities. Those capacities would involve evaluating different pieces of scientific evidence and judging their relative importance in making decisions around key issues of personal and social importance. Along this line, and closely following the French linguist Christian Plantin (2005, 2011), Pablo Archila states that

> argumentation has been positioning itself as a social imperative, if it is considered as a way to treat differences, eliminating them, or moving them forward towards collective welfare […]; [education for citizenship] can resort to argumentation to justify, on the basis of shared values, the existence of positions on debated issues that are socially sensitive, such as racism, abortion, the defence of the environment, war, women and children, animal rights, among others. (Archila 2012, p. 364; my translation)

Thus, there is strong consensus that 'student participation in argument develops communication skills, metacognitive awareness, critical thinking [reason 1 above],

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[5] An anonymous reviewer of this chapter suggested the inclusion of this remark. Emphasis on this central 'learning to learn' aspect of argumentation is probably a cause for the blurring of its more specific epistemic aspects, linked to the nature of science.

an understanding of the culture and practice of science [reason 2], and scientific literacy [reason 3]' (Cavagnetto 2010, p. 336).

Due to this interest in the diverse contributions of argumentation to science education, in the last decade a vast and rapidly expanding corpus of literature has accumulated in didactics of science.[6] Several possible approaches to the study of argumentation in school science have been put forward, related to the theoretical conceptualisations utilised and to the practical aims sought.[7] In this sense, '[a]ccording to different conceptualizations in this domain [of argumentation studies] instructional accounts to promote argumentative abilities of students also differ considerably' (Böttcher and Meisert 2011, p. 104). It could be added that, in consistency with those different conceptualisations, the 'natures' of science propounded for instruction also differ.

Underneath the variety of approaches, different intellectual threads can be recognised. A number of disciplines, fields of study or theoretical frameworks have converged to help didacticians of science in the task of defining, fostering and assessing argumentation in science education.[8] Nevertheless, the epistemic perspective, where an HPS[9] background would be of use, has been somewhat obscured by active discussion from linguistic, cognitive, ethnographic or pedagogical perspectives. Indeed, as stated above, most research around the place of argumentation in science education has been developed within the area of 'research with a focus on classroom discourse during the teaching and learning of science' (von Aufschnaiter et al. 2008, p. 103), with some studies also focussing on written argumentative products (cf., Adúriz-Bravo et al. 2005; Bell and Linn 2000; Erduran et al. 2004). Thus, the interest has been mainly put in the strictly *linguistic* aspects.

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[6] In Archila (2012), Buty and Plantin (2008a), Erduran and Jiménez-Aleixandre (2008), Jiménez-Aleixandre (2010), Jiménez-Aleixandre and Díaz de Bustamante (2003), Khine (2012), Nielsen (2011), Sampson and Clark (2006, 2008), and Sanmartí (2003), there are rather comprehensive literature reviews on the subject, with more than three hundred references in English, French and Spanish.

[7] For example: Abell and colleagues (2000), Adúriz-Bravo and colleagues (2005), Bell and Linn (2000), Driver and colleagues (2000), Duschl (1990), Duschl and Osborne (2002), Fagúndez Zambrano and Castells Llavanera (2009), García Romano and Valeiras (2010), Henao and Stipcich (2008), Islas and colleagues (2009), Konstantinidou and colleagues (2010), Lawson (2003), Linhares Queiroz and Passos Sá (2009), Newton and colleagues (1999), Osborne and colleagues (2001), Revel Chion and colleagues (2005), Ruiz and colleagues (2011), Sanmartí (2003), Sasseron and Carvalho (2011), and Schwarz and colleagues (2003).

[8] See, for instance, Cadermártori and Parra (2000), Candela (1999), Kuhn (1992), Martins (2009), Mason and Scirica (2006), and Pontecorvo and Girardet (1993), among a host of others, for theoretical foundations ranging from psychologist James F. Voss to semiotician Mikhail Bakhtin, going through argumentation theorist Frans van Eemeren and social anthropologist Jean Lave.

[9] I will here use the acronym HPS (history and philosophy of science in/for science education) to denote the area of research within didactics of science that strives to incorporate a metatheoretical perspective in science education (cf., Matthews 1994/2014, 2000). This area would mainly draw from the meta-sciences (philosophy, history and sociology of science), but it would also include elements from the science studies and from other 'less disciplined' metatheoretical endeavours, such as science-technology-society (STS), feminist epistemologies or public understanding of science.

In order to transcend this discursive approach, and to recover substantive links between scientific argumentation and metatheoretical reflection on the nature of science, the aim of this chapter is threefold:

1. Identifying and characterising a subset of literature on argumentation in science education where connections to HPS are apparent or can be unproblematically proposed.
2. Spotting there some of the 'bridges' that are explicitly announced or can be implicitly recognised between mainstream HPS and argumentation in the science classroom, such as evidence-based science education, inquiry, nature of science and scientific explanation and justification.
3. On the basis of the two previous points, 'revisiting' some defining aspects of school scientific argumentation with an epistemic perspective, using categories from HPS that may help in the re-conduction of this issue towards convergence with the area of research of this handbook.

As stated above, the current state of development of the emerging line of research around argumentation within didactics of science is impressive, with several hundreds of papers accumulated (cf., Osborne et al. 2012). Consequently, this chapter does not purport to be a comprehensive literature review in all aspects of argumentation,[10] but rather an account of some productions on school scientific argumentation selected due to their possibility to be 'tuned' to the discussions in our own field, HPS. At the same time, the chapter makes an effort to incorporate into the English-speaking discussion in science education some less visible contributions from the continental, 'Didaktik' tradition (cf., Westbury et al. 2000), to a great extent shared by Germanic, Scandinavian, Latin, Greek and Slavic countries.

45.2 The Notion of School Scientific Argumentation

In this chapter, I call 'school scientific argumentation' (cf., Adúriz-Bravo 2011) the argumentative *processes* (i.e. discursive practices) and *products* (i.e. texts in any semiotic register) that occur in the science classrooms of all educational levels – from Kindergarten to University. In this sense, 'argumentation' here refers both to argu*ment* and argu*ing*, i.e. 'the product, statement or piece or reasoned discourse […] and […] the social process or activity' (Jiménez-Aleixandre and Erduran 2008, p. 12).

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[10] The tables of content of the three available *handbooks* on school scientific argumentation (i.e. Buty and Plantin 2008a; Erduran and Jiménez-Aleixandre 2008; Khine 2012) can give readers an idea of the current lines of research within the strand. These lines would be, once chunked and retitled, argumentation, learning and concept formation; argumentation, learning environments and communities of practice; argumentation, discourse and language games; argumentation, social interactions and meaning negotiation; argumentation and scientific reasoning; argumentation and socioscientific and moral issues; argumentation and science teacher education; argumentation-based instruction; argumentation quality and assessment; and argumentation and epistemic criteria and practices.

From now on, the chapter will be restricted to the argumentation intentionally generated so that students understand and use scientific theories and models for problem-solving within the boundaries of science. What we can call ‘socioscientific argumentation’ will thus be purposefully excluded, since such kind of argumentation has epistemological traits that cannot be totally captured with the elements discussed in this chapter.[11] Among those special traits of socioscientific argumentation, the following could be mentioned: (a) it is heavily context dependent; (b) it usually results from a co-construction by different utterers; (c) it draws upon moral reasoning; and (d) it does not have as main reference ‘the scholarly societies acknowledged to create and validate scientific knowledge’ (Tiberghien 2008, p. xi), but rather social representations and knowledge from different disciplined and undisciplined sources.

The installation of school scientific argumentation as a central issue of science education can be attributed to what may be seen as an ‘argumentative turn’. That is to say, in the last four decades or so, social sciences, and social interests and debates more generally, seem to be moving in the direction of recognising argument and arguing as key features of our post-modern culture in general and of science in particular. Within the argumentative turn, at least three fields that are important for the endeavours of our community of didacticians of science are shifting towards the consideration of the nature of science as strongly argumentative (cf., Adúriz-Bravo 2010):

1. Firstly, new school science curricula point at scientific argumentation as one of the central competencies to be achieved during compulsory education (cf., Buty and Plantin 2008b; Jiménez-Aleixandre and Federico-Agraso 2009). True citizenship is now being characterised by the ability to engage in (socio-)scientific argumentation and to make informed decisions in fields such as environment, climate, energy, sustainability, public and individual health, food and pollution. It could be argued that these curricula express the current social expectations (i.e. the ‘social imperative’ of which Archila [2012] talks) on the education of critical citizens.
2. Secondly, meta-sciences (philosophy, history and sociology of science) and other metatheoretical perspectives have turned towards the study of the scientific language and have directly challenged the received view that considers it an *ex post facto* labelling system that operates after clear and distinct ideas and concepts have been construed. The language of science is now ‘problematised’; it is seen as a rich and complex set of cultural tools that enable semiosis: giving meaning to the natural world and making sense to the users (cf., Sutton 1996, who speaks about language as an ‘interpretive system’). Within this context, where a ‘linguistics of science’ is emerging, argumentation is considered a paradigmatic genre in science.

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[11] For authoritative works on argumentation in connection with socioscientific issues, see Zeidler (2003, especially Chaps. 3, 4, 5, and 7) and Sadler (2011, especially Chaps. 11 and 12).

3. And thirdly, with direct bearings to the corpus of knowledge examined in this chapter, didactics of science and other educational studies (learning psychology, classroom ethnography, etc.) have been paying increasing attention, at least in the last 15 years, to the so-called cognitive-linguistic ability (cf., Sanmartí 2003) of scientific argumentation, analysing ‘argumentation discourse in science learning contexts’ (Jiménez-Aleixandre and Erduran 2008, p. 4). The science classroom is now depicted as a cultural system where language has a structuring function and thus ‘talking science’ (cf., Lemke 1990) should be turned into content to be explicitly and specifically taught.

It could be contended that the first of these three fields – new curricula that express new social mandates – has installed argumentation as a central issue for science education; the second field – metatheoretical studies on the language of science – has enriched our image of the nature of science by acknowledging the existence of argumentative games; and the third field – educational studies on argumentation – has equipped didactics of science with theories and methods, and it has at the same time promoted the over-emphasis on the discursive aspects.

Consistent with this prior analysis, it is the contention here that the notion of school scientific argumentation can be broadly characterised through resorting to the idea of evidence; it can then be more concretely defined using a distinct linguistic stance, and, afterwards, it can be inspected from a metatheoretical perspective, ascertaining its participation in the construction of science.

For a broad definition, this chapter resorts to Jiménez-Aleixandre and Díaz de Bustamante (2003), who see scientific argumentation as ‘the ability to relate data and conclusions, to evaluate theoretical propositions in the light of empirical data or data from other sources’ (p. 361, my translation).

The term ‘evidence’ will be used here to designate not only empirical data arising from observation and experimentation but also theoretical reasons, authoritative claims, elements from worldviews, ethical considerations, stakeholders’ interests and other kinds of ‘supporting assertions’.[12] Thus, evidence collectively denotes the *grounds* provided to justify the assertion or claim that is being argued for:

> Evidences are the observations, facts, experiments, signs, samples, or reasons with which we intend to show that a statement is true or false. (Jiménez-Aleixandre 2010, p. 20; my translation)

This initial, general, characterisation identifies scientific argumentation as one of the basic processes of knowledge construction, a process that

> recasts the role of evidence and data in scientific classrooms: rather than being used to demonstrate the scientific canon or even to guide students to construct correct scientific principles, it is the grounds on which claims – generated by students in the process of argumentation – are warranted. (Atkins 2008, p. 63)

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[12] A conception of evidence that is broader than ‘experimental data’ on the one hand better captures the history of scientific activity and on the other hand is essential in order to account for argumentation in socioscientific contexts.

This approach to argumentation represents a sophistication of the definition presented in Sect. 45.1, at least in the line of its first highlighted element – ‘arriving at conclusions […] through a process of logical reasoning’ – as it underlines the *functional* role played by evidence in the derivation of such conclusions.

For a more specific definition, it is useful to adhere to the one presented by the research group LIEC (*Lectura i Ensenyament de les Ciències*, ‘Reading and Science Teaching’) from the Universitat Autònoma de Barcelona in Spain:

> Argumentation is a social, intellectual, and verbal activity that allows justifying or rebutting a claim; it consists of making statements taking into account the recipient and the aim with which they are transmitted. In order to argue, one must choose between different options or explanations and reason the criteria that permit evaluating the chosen option as the most adequate. (Sanmartí 2003, p. 123; my translation)

According to this strongly linguistic approach, arguing would then be elaborating a text (be it oral, written or multi-semiotic) with the aim of changing the epistemic value of the ideas sustained by an audience (or a single recipient) on an issue or matter. Such a change is sought through providing meaningful reasons so that the audience or recipient see that a new set of ideas is ‘justified’ by evidence in its most general sense, introduced above. The weight attributed here to justifying and convincing to some extent mirrors the other two highlighted elements of the definition in Sect. 45.1: ‘a process […] that includes debate and persuasion’.

This theoretical conceptualisation on scientific argumentation, and a host of others to which didactics of science has resorted, stem from ‘a range of relevant disciplines’ (Bricker and Bell 2008, p. 474). According to Bricker and Bell’s (2008) classic article, the most relevant of such disciplines are formal logic, argumentation theory, science studies (and here the philosophy of science would be included) and the ‘learning sciences’. The next paragraphs draw on the contributions of the first three, which are more pertinent for an HPS approach.

In order to characterise scientific argumentation from a didactical point of view, some ‘tensions’ (cf., Adúriz-Bravo 2010) that underlie the notion of argumentation – within and outside the science classroom – need to be discussed; such tensions are unveiled when analytical tools from the aforementioned disciplines are employed. It could be safely said that these tensions have many times been dismissed or underrepresented in the literature of didactics of science, partly perhaps as a result of the hegemony of the so-called Toulmin’s argumentation pattern (or ‘TAP’) as the preferred theoretical and methodological framework (see Sect. 45.2.1). The generalised use of TAP has fixed the discussion around semiformal reconstructions of arguments akin to those propounded by the theory of argumentation of mid-twentieth century or, rather, around a highly stylised didactical version of such reconstructions.

The four tensions that are developed in the following subsections are:

1. The opposition between two intellectual traditions to study argumentation, namely, the *Anglo-Saxon* (e.g. Stephen Toulmin, Henry W. Johnstone Jr., Ralph H. Johnson, Douglas Walton, G. Thomas Goodnight) and the *continental* (e.g. Arne Naess, Chaïm Perelman, Oswald Ducrot, Frans van Eemeren & Rob

Grootendorst, Christian Plantin).[13] These two traditions would represent complementary ways of going beyond the classical, neo-Aristotelian, approach to the study of arguments: in the first case, by 'softening' the requirements of syllogistic logic, and in the second, by opening the floor to pragmatic and rhetorical constraints.

2. *Logic* versus *dialogic* argumentation. The opposition between two extreme forms of argumentation – argumentation as explanation and argumentation as debate – is traditionally presented as the existence of 'analytical' and 'dialectical' arguments.[14] Such opposition is usually conflated with the distinction between the use of formal and informal logic in order to analyse such arguments, revised in the fourth tension.
3. Arguing as *explaining* versus arguing as *justifying*, partially connected to the former, and pointing at Jiménez-Aleixandre and Erduran's (2008, p. 9) distinction between producing scientific knowledge about the world and giving 'rhetorical significance' to that knowledge. The 'explanatory' part of argumentation, in this context, would entail making sense of a phenomenon on the basis of data, while the 'justification' part would mean supporting the claim that the data are consistent with the proposed explanation and therefore convincing an audience of its validity (cf., Osborne and Patterson 2011, p. 629, who use similar phrasings, but sharply separate these two operations).
4. Arguments as texts of *'harder'* versus *'softer' syntax*. This refers to the clash between the existence of sanctioned patterns with an a priori rationality dictated by formal logic, leading to heavily 'idealised notions of arguments' (Jiménez-Aleixandre and Erduran 2008, p. 15), and the pragmatic use of what we can call *para-logical* (i.e. ampliative) techniques to capture argumentation 'as it is practiced in the natural languages' (Jiménez-Aleixandre and Erduran 2008, p. 14). Among these 'real' argumentative practices, scientists', teachers' and students' discourse would be included.

45.2.1 Anglo-Saxon Versus Continental Approach to Argumentation

Since the three traditions that follow this first one can be said to hinge to some extent on an *ab initio* divergence between theoretical approaches to argumentation, this subsection is longer and more detailed than the rest; in those, cross-references to the ideas exposed here are made.

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[13] For other authors not mentioned in this list, see Reygadas and Haidar (2001), Santibáñez (2012).

[14] This opposition is in turn based on Aristotle's division of 'perspectives' on argumentation that has been thoroughly used in continental studies and retrieved by the Anglo-Saxon tradition: logical, dialectical and rhetorical (cf., Harpine 1985; van Eemeren and Houtlosser 2003). The chapter concentrates only in the first two classes of arguments.

The Anglo-Saxon tradition in argumentation studies was long based on the assumption that arguments are more or less ‘syllogistic’ (i.e. deductive-like) in nature (this restrictive requirement of ‘deductivity’ is still retained in the general definition of argumentation presented in Sect. 45.1). Arguments were usually portrayed as a tight structure in which a key assertion is logically inferred from a set of supporting assertions (Asti Vera and Ambrosini 2010). As Stephen Toulmin critically remarks,

> [T]he assumption […] made by most Anglo-American academic philosophers [was] that any significant argument can be put in formal terms: not just as a syllogism, since for Aristotle himself any inference can be called a ‘syllogism’ or ‘linking of statements’, but a rigidly *demonstrative deduction* of the kind to be found in Euclidean geometry. Thus was created the Platonic tradition that, some two millennia later, was revived by René Descartes. (Toulmin 2003, p. vii; my emphasis)

Accordingly, classical argumentation theory among Anglo-Saxon authors more or less overlapped in scope and methods with the discipline of logic – the main aim being to ascertain the *validity* of arguments using formal techniques.

In the Anglo-Saxon tradition, the main connecting threads would be the attention paid to the *syntactic* aspects of the language used to argue and the aim of analysing individual propositions and their structural relations in order to justify and assess theoretical arguments, dialogic exchanges and informed judgements set against the backdrop of their social contexts. The evolution of this tradition could be seen as an expansion of the traditional apparatus to study argumentation – which strictly resorted to formal logic – towards the use of ‘para-logical’ tools, moving then onto ‘informal logic’. The focus is thus to capture ‘natural’ arguments, to formulate

> [the] statements [referred to in those arguments] in a ‘normal’ (philosophical, universal) language in some canonical form [, since a]fter 2,300 years of formal logic, [argumentation theory is] still infinitely remote from having a clear idea of what such a language should look like. (Bar-Hillel 1970, p. 204)

This Anglo-Saxon approach to argumentation will be here characterised through rapidly examining the work of the British-born philosopher of science Stephen Toulmin, with a peripheral mention to the Canadian argumentation theorist Douglas Walton and the American educational psychologist Deanna Kuhn.

Toulmin’s (1958) framework hinges upon a naturalistic approach to the rationality of practical arguments (which he calls ‘substantial’ arguments). Substantial arguments are opposed to ‘theoretical’ arguments, which are analytic and necessary. This means that, in the latter, the argued assertions are the conclusions of *sensu stricto* inferences; such assertions are deductively connected to a set of premises providing the evidence for it (hard data or other grounds, but always satisfying the relationship of logical necessity with the conclusion). Thus, what is being sustained is already ‘contained’ in what we know.

Substantial arguments, on the contrary, seek to offer ‘justification’ for an assertion that is deemed to be of interest, in a specified and recognisable context. Thus, Toulmin suggests going beyond formal logic when modelling arguments and proposes an ‘argumentation pattern’ with tightly interrelated components:

the *claim* (which is the statement in need of justification), *data* to support such claim and a *warrant* that allows the 'legitimate' transition from data to claim. Even more 'real' arguments in the natural language are heavily modalised and include qualifiers, rebuttals and backing to the warrant.

It could be stated that, in Toulmin's framework, the claim – 'conclusion' *sensu lato* – has more content than that of the evidences provided, and thus it is only partially sustained by them. Accordingly, it is convenient to portray the 'movement' from the premises containing the evidence to the conclusion as an ampliative inference, which should be captured with inductive, analogical, abductive, etc. reasoning patterns (cf., Stadler 2004; Diéguez Lucena 2005).

In turn, the goal of Walton's (1996) framework is more related to understanding persuasive arguments, for example, in legal contexts. Walton is thus more interested in *dialogic*, conversational argumentation (see next subsection), where 'actors exchange replies and counter-replies' (Asti Vera and Ambrosini 2010, p. 133; my translation). Walton's *schemes* for 'presumptive reasoning' refer to strategies used in hypothetic, non-demonstrative, argumentation. To capture those schemes, he enumerates a variety of categories; for instance, he talks about 'arguments based on experts' opinions', which might be instrumental both for scientists' science and school science. *Pertinence* of the utterances – and of the reasons given therein – is a key theoretical element of his framework.

As a complement to the general Anglo-Saxon perspective, D. Kuhn (1993, 2010), moving markedly away from philosophical and linguistic considerations, proposes a conceptualisation of science and of science education as argumentative endeavours that resorts to psychological and cognitive foundations. In this sense, she is a good example of contributions to argumentation from the 'learning sciences'.

Opposing the Anglo-Saxon tradition, we can talk of a 're-emergence' of a continental approach to argumentation studies, which occurs after World War II and is of course favoured by external, socio-cultural, factors (cf., Jiménez-Aleixandre and Erduran 2008). Chaïm Perelman's life story – he was a Polish Jew who immigrated to Brussels – is a good example of this. The continental tradition will here be represented in the works of the expert in rhetoric Perelman, the Dutch scholars in 'speech communication' Frans van Eemeren and Rob Grootendorst and Christian Plantin. The connecting threads of this tradition would be the introduction of the audience as a key element and the attention to pragmatic and rhetorical aspects.

Perelman publishes, together with Lucie Olbrechts-Tyteca, his *Traité de l'argumentation* in 1958 (the same year of Toulmin's *The uses of argument*). In this book, the authors propose a 'new rhetoric', understood as an art of persuading and convincing; with this, they also intend to abandon formal logic in the evaluation of argument validity. But, differing from the Anglo-Saxon perspective, persuasion is highlighted; in order to characterise arguments, Perelman constructs new concepts around this idea, such as argumentative force and relevance or the 'intensity of adherence of an audience'. The introduction of the audience as 'a genuine actor in the argumentative phenomenon' (Asti Vera and Ambrosini 2010, p. 110; my translation) is generally considered to be Perelman's main contribution.

Van Eemeren and Grootendorst, at the Universiteit van Amsterdam, develop what they call a *pragma-dialectical theory* of argumentation; like Perelman, they seek to analyse and assess argumentation as a natural practice of language. Pragma-dialectics takes into account the fact that arguments are usually presented within interactive, dialogic discussion. These authors also confront the use of syllogistic structures to study argumentation, since formal logic would be opaque to the subtleties of the social practice of arguing. Scientific argumentation would also need this approach, since scientists direct their arguments to convince peers (or other audiences) so that they accept the point of view that is being offered. Carlos Asti Vera and Cristina Ambrosini (2010) recognise a very 'fecund' starting point in pragma-dialectics, since 'it proposes not abstracting arguments of any of their dimensions, in order to analyse and evaluate them as they are presented in the social theatre, in their empirical, dialogic and contextual determinations' (p. 133).

Plantin is also interested in a rhetorical study of dialogic argumentation (he calls it 'dialogale' in French: cf., Plantin 2011) and again focuses on persuasion as one of its central characteristics. He interprets argumentation as a way of producing speech in situations where doubt, debate and confrontation predominate. It is interesting to remark that Plantin wants to redeem rhetoric from its reputation as a 'sorceress' (Buty and Plantin 2008b, p. 21); according to him, rhetoric has been stereotypically discredited, being repeatedly associated with manipulation, void words and politicians' clichés (for these he uses the very graphic French expression of 'langue de bois').

45.2.2 Logic Versus Dialogic Argumentation

What I call 'logic argumentation' – where arguments are practically confounded with explanations or inferences – can be described, using Richard Duschl's terminological choices (cf., Duschl et al. 1999; Duschl 2008), as the production of analytical arguments. These arguments are grounded in (formal) logic, and they constitute a movement from a set of premises to a conclusion (cf., Asti Vera and Ambrosini 2010). What I call 'dialogic argumentation' – where arguing is seen as exchange of ideas or confrontation – fits with the idea of dialectical arguments, which are 'those that occur during discussion or debate and involve reasoning with premises that are not evidently true' (Duschl 2008, p. 163). It could arguably been said that it was in order to understand this latter kind of arguments that the field of (new) argumentation theory emerged in the 1950s, somewhat vanishing its boundaries with informal logic.

This broad distinction made under this tension can be related to the two major scholarly approaches to argumentation in Sect. 45.2.1 as follows: the stereotypical Anglo-Saxon approach was almost restricted to analytical arguments and logic argumentation (as is apparent in Toulmin's critique), while the best-known continental frameworks over-emphasised dialectical arguments and dialogic argumentation. This simplified, one-to-one relationship tends to relax in more recent texts.

For didactical purposes, it seems convenient to blur this watertight distinction and consider that school scientific argumentation combines in itself the long-standing Greco-Latin traditions of arguing as producing ‘any piece of reasoned discourse’ (Jiménez-Aleixandre and Erduran 2008, p. 12) and arguing as ‘dispute or debate between people opposing each other with contrasting sides to an issue’ (Jiménez-Aleixandre and Erduran 2008, p. 12). Thus, on the logic side, argumentation evokes the etymological meaning of the Latin verb ‘arguere’: ‘make clear through discourse’; such meaning stems from the Indo-European root ‘arg-’, meaning ‘brilliant’ (conserved in modern terms such as the Italian ‘argento’, ‘silver’ or the French ‘argille’, ‘clay’). On the dialogic side, argumentation points at one of the standard meanings of the English verb ‘argue’: ‘discuss’, ‘dispute’ and ‘disagree’. But these two aims of clarifying and debating coexist – and are virtually impossible to divorce from each other – in the language game of argumentation in science.

45.2.3 Arguing as Explaining and Arguing as Justifying

When argumentation is seen as a vehicle for scientific explanation, the emphasis is put on the sharing of theoretical elements that permit us to understand the world. Arguments are seen as ‘solid’, i.e. with a claim well supported by foundations and backings (cf., Asti Vera and Ambrosini 2010), and such a view purports to be context and audience independent.[15] In this first perspective, Toulmin’s idea of warrant is paramount: warrants serve as the explanatory elements; their aim is to give testimony of the legitimacy of the transition from data to claim. Warrants provide general, abstract and *uniform* transitions, which are relatively autonomous of (i.e. not referring directly to) particular sets of data.

When argumentation is seen as an act of speech where justification is demanded and offered (cf., Tindale 1999, who examines this idea based on Michael Billig and Chaïm Perelman), the focus is moved to the recipient’s or audience’s adherence to the claim presented. In this second perspective, more akin to continental studies, ‘argumentation is a feature of social relations and shares in the complexity of those relations’ (Tindale 1999, p. 75).

In science education, the distinction between argumentation as explanation and argumentation as justification can be partially aligned with what Nussbaum and colleagues (2012) call the ‘two faces of [school] scientific argumentation’. According to these authors, argumentation is on the one hand *explanatory*, when it presents and debates scientists’ theories about reality. On the other hand, argumentation is *prescriptive*, when it informs scientific (and socioscientific) debates, where decision-making is often required. These authors distinguish between ‘theoretical discourse, pertaining to what theories of the world best fit the data and practical, deliberative discourse, regarding how to apply those theories to reach practical goals’ (Nussbaum

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[15] This is what Constanza Padilla (2012) calls ‘demonstrative dimension’ of argumentation.

et al. 2012, p. 17). Accordingly, students and teachers together would use scientific arguments in the science classroom to explain theoretically *and* to circulate and share understandings and applications.

45.2.4 Hard and Soft Arguments

This last tension, as advanced above, has to do with the capacity attributed to formal, abstract structures to capture real discourse. The classical, positivistic approach of categorical rationalism 'supposes enthroning formal logic as the *exclusive* model of rationality' (Asti Vera and Ambrosini 2010, p. 110; my translation, emphasis in the original). Through the lens of formal logic, only what we might call 'hard arguments' survive: those that are 'fully explicit [and] neatly packaged into premises and conclusions' (Smith 2003, p. 34).

If one adheres to this restriction, real argumentation practices are almost always subsumed into the realm of material (or informal) fallacies. There is an *ab initio* 'half-empty glass' metaphor operating here, since – from the point of view of hard rationality – most arguments are considered to be logically non-pertinent, only psychologically persuasive, and often intended to deceive (cf. Asti Vera and Ambrosini 2010). Even in the case of (empirical) science, most relevant arguments do not measure up to the extremely restrictive standards of demonstrative argumentation, since they contain in their fabric elements that are not bound by the relationship of necessity, and therefore cannot be completely formalised without consideration of their empirical content.

Two options arise to oppose this 'hard' approach: in the first place, rationality can be resigned altogether, slipping down the irrational slopes of contextualism, relativism or constructivism. A 'third way', which seems more productive for science education, would be to broaden the scope of arguments that can be considered well supported. This third way would imply a 'temperate', non-aprioristic, rationality, which resorts to the use of 'para-logical' techniques, i.e. non-demonstrative patterns of inference such as induction or abduction. Softening the syntax admitted for arguments is, in all cases, allowing a richer study of argumentation as it occurs in the real world. This would constitute a *naturalisation* of argumentation theory.

For this last tension, the link to the Anglo-Saxon-continental dispute is not straightforward. One might be tempted to assume that the Anglo-Saxon approach closes up the number and variety of patterns of argumentation that are admissible and is therefore more identifiable with the idea of 'harder syntax'. This might be the case for the classical studies, those that fall under Toulmin's critique, but it is certainly not applicable to post-Toulminian accounts of scientific argumentation among English-speaking scholars. On the other hand, a pairing of what I have proposed to call 'softer syntax' to continental accounts would be too hasty, since the examination of the structure and components of an argument is seldom a concern among authors who zoom out to rhetorico-pragmatic considerations.

45.3 The Epistemics of School Scientific Argumentation

This section is devoted to dissecting some of the epistemic aspects of school scientific argumentation, aspects that can be theorised through the lens of HPS.[16] The section discusses different constituting elements of the *epistemics* (i.e. epistemology) of argumentation, identified on the basis of a review of the literature in didactics of science that is heavily theory driven. That is to say, the review is guided by an attention to metatheoretical perspectives and especially to the philosophy of science. As it was advanced in the introduction to the chapter, in order to organise such review, possible 'bridges' between argumentation and HPS are defined.

Under the five bridges enumerated here, studies on school scientific argumentation with an interest in one or more particular epistemic aspects are grouped. The studies may or may not present an explicit HPS background, and this will be indicated for each case. The five resulting groups are:

1. *Argumentation as an epistemic practice.* In this first approach, undoubtedly the most exploited one, the bridge consists in identifying argumentation as a paradigmatic example of epistemic practice, i.e. a practice of knowledge construction that gives its character to the scientific activity. Richard Duschl (1998, 2008), Marilar Jiménez-Aleixandre (Jiménez-Aleixandre and Federico-Agraso 2009; Bravo-Torija and Jiménez-Aleixandre 2011), Gregory Kelly (Kelly and Chen 1999; Kelly and Takao 2002), Victor Sampson and Douglas Clark (2006, 2008), and William Sandoval (Sandoval 2003; Sandoval and Reiser 2004; Sandoval and Millwood 2005, 2008), among many others, have advocated for a conceptualisation of argumentation along this line.
2. *Argumentation as a feature of the nature of science.* In this second, more encompassing approach, the bridge consists in describing the 'non-natural' nature of science,[17] at least partially, through inspecting the role that argumentation (both in the senses of explaining and of justifying) plays in doing, thinking and talking about the natural world. Authors who can be located within this perspective[18] identify science not with the 'discovered' facts of the world, but rather with an extremely elaborate inferential and discursive construction regarding the ways in which scientists appropriate and transform those facts.
3. *Argumentation in scientific inquiry.* In this third approach, school science is designed as an inquiry-based endeavour aiming at genuine scientific literacy (see public policy documents such as AAAS 1993; NRC 1995). The bridge here

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[16] The name of this section is a paraphrasis of an expression by Sandoval and Millwood (2008, p. 72).

[17] Both Lewis Wolpert (1992) and Lydia Galagovsky (2008) refer to this 'non-naturality' of science in the titles of their books. Nevertheless, the meanings of the expressions that they use are quite distinct from each other. Wolpert's thesis, positivistic in its foundations, is that science is a way of thinking far away from common sense. Galagovsky's compilation of chapters aims at showing how science is a very elaborate human construction and not a mere expression of the way the world is.

[18] For example, Allchin (2011), Duschl (1990, 1998), Hodson (2009), Lawson (2003, 2005, 2009), and McDonald (2010)

is the attention to the inclusion of argumentative skills in such an endeavour. A grasp of the nature of science in science education

> involves understanding *how knowledge is generated, justified, and evaluated* by scientists and *how to use such knowledge to engage in inquiry* in ways that reflect the practices of the scientific community. (Clark et al. 2010, p. 1; emphasis in the original)

The two elements of the nature of science italicised in this quote could be somehow referred to the two poles of tension 3: on the one hand, students need to comprehend the epistemic practice of knowledge generation (explanation); on the other hand, students need to apply that knowledge in school scientific inquiry (justification). Proposals along this line[19] strive to meaningfully connect argumentation and inquiry through the introduction of evidence- and argument-based practices in the science classroom.

4. *Model-based argumentation.* In this fourth approach,

> the general model-based perspective in […] the philosophy of science [is used in order to] understand arguments as reasons for the appropriateness of a theoretical model which explains a certain phenomenon. (Böttcher and Meisert 2011, p. 103)

The bridge here is that argumentation is regarded as a tool to assess and apply the models that constitute the content of school science. Authors who use this perspective (Adúriz-Bravo (2011), Böttcher and Meisert (2011) and much less directly Lehrer and Schauble (2006), who talk about 'model-based reasoning' and Windschitl et al. (2008), who talk about 'model-based inquiry') conceptualise models using *semantic* tools from the philosophy of science of the last three decades.

5. *Argument-based school science.* This fifth approach is rather unspecific; it suggests that argumentation should be a substantive part of the (social) activity in the science classroom (and in science teacher education). Authors adhering to this perspective talk about 'argumentation-based' teaching or instruction.[20] The bridge here are the reasons provided in favour of this position, drawn mainly from the sociology of science (with references to Helen Longino or Bruno Latour, for instance) and to a lesser extent from other metatheoretical perspectives.

A proviso should be made here: in the very biased selection of literature in which the bridges between argumentation and HPS have been identified, papers that use HPS elements for the design of instructional units and materials, but then fail to use those elements to characterise or justify the presence of argumentation in those units and materials, were purposefully excluded. For instance, Bell and Linn (2000), Monk and Osborne (1997) and Revel Chion and colleagues (2009) use the history and philosophy of science to lay the foundations for the teaching of different

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[19] For example, Clark and colleagues (2010), Duschl and Grandy (2008), Sampson and Clark (2007), Sandoval and Reiser (2004), and Windschitl and colleagues (2008).

[20] Cf., Driver and colleagues (2000), Izquierdo-Aymerich (2005), Newton and colleagues (1999), Ogunniyi (2007), and Ogunniyi and Hewson (2008).

scientific topics (Darwin's ideas, light, the bubonic plague, etc.), and then – more or less independently of those foundations – they propose to implement argumentation as a teaching strategy.

In the subsections that follow, the five aforementioned bridges are explicated through one or two epitomic examples of each of them.

45.3.1 Argumentation as an Epistemic Practice

Richard Duschl's work locates explanation at the vertex of the pyramid of the activities in science (cf., Duschl 1990), identifying it as a privileged aim of the scientific enterprise. In his framework, and following Gregory Kelly and Deanna Kuhn, argumentation would constitute one of the most favoured epistemic (i.e. knowledge-producing) practices. Consistent with this conceptualisation of scientists' science, Duschl proposes, for school science,

> [s]hifting the dominant focus of teaching from what we know (e.g., terms and concepts) to a foc[us] that emphasizes how we know what we know and why we believe what we know (e.g., using criteria to evaluate claims). (Duschl 2008, p. 159)

School science would then require 'epistemic apprenticeship' (Jiménez-Aleixandre and Erduran 2008, p. 9): students should appropriate criteria to evaluate arguments in the light of evidence. Accordingly, science in the classroom could be structured as a set of 'epistemological and social processes in which knowledge claims can be shaped, modified, restructured and, at times, abandoned' (Duschl 2008, p. 159). Duschl talks about 'knowledge-building rules' that represent or embody the epistemic practices of the community formed by students and teacher(s).

Thus, the core of this conceptualisation of argumentation as an exemplar of educationally valuable epistemic practice would be captured in questions such as

> What counts as a claim? What counts as evidence? How do you decide what sort of evidence supports, or refutes, a particular claim? How are individual claims organized to produce a coherent argument? What kinds of coordination of claims and evidence make an argument persuasive? (Sandoval and Millwood 2008, p. 72)

One of the most favoured strategies in the studies allocated in this first group has been to recognise epistemic *statuses*, *criteria* or *levels* in students' argumentative practice, with the aim of 'assessing the nature or quality of arguments in the context of science education' (Sampson and Clark 2008, p. 449). Such assessment is done, for instance, in terms of their complexity, robustness, validity, etc.

For this first bridge, explicit recurrence to authors from the area of HPS has been somewhat low. In Sandoval and Millwood (2008), for instance, of almost 30 cited references, only three are to authors with a meta-scientific perspective: Philip Kitcher, Bruno Latour and Stephen Toulmin. In Duschl (2008), of around 45 cited references, again only three are to texts in the realm of HPS (Derek Hodson, Nicholas Rescher and Toulmin). In Sampson and Clark (2008), among circa 65 references, only two 'meta-scientists' feature: Latour and Thomas Kuhn. The relationship between favouring argumentative practices in science education and metatheoretically characterising those as epistemic practices is therefore *indirect*: most authors that develop this first bridge refer to some seminal texts in didactics of science (e.g. Driver et al. 2000; Duschl and Osborne 2002; Kelly and Takao 2002) that have acknowledged the philosophical foundations of that relationship, but then do not go on developing such foundations.

45.3.2 Argumentation as a Feature of the Nature of Science

There is a substantive connection between this second approach and the first one, since a widespread hypothesis in science education considers that 'students' epistemological beliefs [i.e. their conceptions on the nature of science] are developed through their own epistemic practices of making and evaluating knowledge claims' (Sandoval and Millwood 2008, p. 85). Epistemic practices in general, and argumentation in particular, would then be, at the same time, a specific feature of the nature of science (cf., Hodson 2009, Chap. 8) and a powerful means to access to a coherent and robust conceptualisation of such nature.

Both Jonathan Osborne and Sibel Erduran, in many of their papers (cf., Erduran et al. 2004; Osborne et al. 2001), have enumerated different links between the nature of science and argumentation. Osborne and colleagues (2001), for instance, subordinate those links to the need to teach the nature of science *explicitly*,[21] since 'contact with school science is insufficient to generate an understanding of how science functions' (p. 69). For such teaching, argumentation becomes a privileged tool, insofar as it permits presenting students with opportunities to examine and discuss epistemological issues such as evidence, prediction, analytical thinking, controversy, reasoning, evaluation and critical thinking.

From a more focussed point of view, Anton Lawson points out that nature-of-science instruction should teach to science students 'that the best [scientific] argument considers all of the alternatives and explicitly includes the relevant evidence and reasoning supporting and/or contradicting each' (Lawson 2009, p. 337). He suggests introducing, in science education, what he calls an 'if/then/therefore' argumentative pattern. His theoretical framework, which he deems valid both for scientists' science and for school science,

> distinguishes among an argument's declarative elements (i.e., puzzling observations, causal questions, hypotheses, planned tests, predictions, conducted tests, results, and conclusions) and its procedural elements (i.e., abduction, retroduction, deduction, and induction). (Lawson 2009, p. 358)

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[21] As one of the anonymous reviewers of this chapter pointed out, considering the nature of science or argumentation important goals of science education does not imply deciding to teach these issues explicitly. The contention that school scientific skills are not developed by 'exposure' and deserve 'direct instruction' is still debated; nevertheless, such contention seems to be finding some support coming from recent empirical studies (e.g. Kirschner et al. (2006), at a general level, and McDonald (2010), for the case of nature of science and argumentation).

It should be noted that Lawson provides extensive HPS backing to his framework, using the history of science in order to construct case studies of scientific reasoning, argumentation and discovery and – to a lesser extent – the philosophy of science to understand those three processes.

In my own work, I portray scientific argumentation as the textual counterpart of the epistemic operation of scientific explanation (Adúriz-Bravo 2005, 2010, 2011). I define argumentation as the *subsumption* of some phenomenon of the natural world under a theoretical model (in the sense of the semanticist family), which is seen as a good candidate to 'explaining' it (and hence there is direct connection with bridge 4). Similarly to Lawson, my argument is that some discoveries and inventions, as reported by scientists through history, can be reconstructed as cases of abductive and analogical thinking; these kinds of inferences would then be the mechanism to subsume the 'phenomenon-case' under a 'model-rule'. I distinguish between abduction *sensu lato*, as any ampliative, non-monotonic, inference producing or evoking hypotheses and abduction *sensu stricto*, as a 'reverse' deductive schema *à la* Peirce (cf., Adúriz-Bravo 2005; Aliseda 2006; Samaja 1999).

45.3.3 Argumentation in Scientific Inquiry

School scientific inquiry can be broadly conceptualised as a 'knowledge building process in which explanations are developed to make sense of data and then presented to a community of peers so they can be critiqued, debated and revised' (Clark et al. 2010, p. 1). In this sense, inquiry would function as a reconciliation of the two poles of the second (logic-dialogic) and third (explain-justify) tensions. Within this framework of ideas, argumentation nicely fits when understood as

> the ability to examine and then either accept or reject the relationships or connections between and among the evidence and the theoretical ideas invoked in an explanation or the ability to make connections between and among evidence and theory […]. (Clark et al. 2010, p. 1)

From this perspective, argumentation is seen as an artefact to develop and evaluate explanations (cf., Kuhn Berland and Reiser 2009; Osborne and Patterson 2011; Windschitl et al. 2008). In other words, in this third approach the practices of explanation and argumentation would be *complementary*:

> First, explanations of scientific phenomena can provide a product around which the argumentation can occur, as proponents of an explanation attempt to persuade their peers of their understandings. Second, argumentation creates a context in which robust explanations – those with which the community (the students) can agree – are valued. (Kuhn Berland and Reiser 2009, p. 28)

For this third bridge, it should be noted that Kuhn Berland and Reiser's (2009) paper has an extensive and developed HPS background. These authors show how several philosophers of science, in the last six decades, extended

> [t]he everyday sense of argumentation[, which] typically suggests a competitive interaction in which participants present claims, defend their own claims, and rebut the claims of their

> opponents until one participant (or side) "wins" and the other "loses". [Instead, i]ndividuals compare conflicting explanations with the support for those explanations and work to identify/construct an explanation that best fits the available evidence and logic. (Kuhn Berland and Reiser 2009, pp. 27–28)

45.3.4 Model-Based Argumentation

In model-based argumentation, scientific arguments are understood as the 'reasons for the appropriateness of a theoretical model which explains a certain phenomenon' (Böttcher and Meisert 2011, p. 103), and argumentation 'is considered to be the process of the critical evaluation of such a model if necessary in relation to alternative models' (Böttcher and Meisert 2011, p. 103). Here, the second and fourth tensions are apparent: on the one hand, models that explain are judged in terms of the reasons for their justification; on the other hand, critical evaluation of the appropriateness of those models would require the use of some analytical tools arising from classical or modern logic.

Central to this approach to school scientific argumentation is the thesis that

> [t]he model-based theory represents a suitable theoretical framework for describing arguments and argumentation referring to the similarity between models and empirical data as the central reference for model evaluation. (Böttcher and Meisert 2011, p. 137)

Derek Hodson (2009) provides a detailed description of the role attributed to argumentation in a model-based depiction of the nature of science. Closely following Ronald Giere (Giere 1988; Giere et al. 2005), he states that

> [r]eaching consensus about the most acceptable model involves a cluster of interacting, overlapping and recursive steps: (i) collection of data via observation and/or experiment, (ii) reasoning, conjecture and *argument*, (iii) calculation and prediction, and (iv) critical scrutiny of all these matters by the community of practitioners. Language plays a role in all these steps […]. As an integral part of these activities, *arguments* are constructed and evaluated at a number of different levels. (Hodson 2009, p. 259; my emphasis)

Such description, explicitly based on HPS, justifies the use of argumentative strategies within the framework of model-based science education.

From a slightly different perspective, but also stressing the role of models in scientific argumentation, Jiménez-Aleixandre (2010) focuses on 'arguments on explanatory models', stating that such arguments intend to identify cause-effect relations in the explanations and interpretations on natural phenomena.

45.3.5 Argumentation in School Science

School scientific argumentation is brought to the centre of the arena of teaching practices ('pedagogy') when the pre-eminently *empirical* conception of students' activity in the science classroom is abandoned in favour of a more theory-laden, social and discursive depiction of school science. Rosalind Driver and her colleagues (2000) accurately explain this shift in the following quote:

> Our contention is that, to provide adequate science education for young people, it is necessary to reconceptualize the practices of science teaching so as to portray scientific knowledge as socially constructed. This change in perspective has major implications for pedagogy, requiring discursive activities, especially argument, to be given a greater prominence. Traditionally, in the UK (and other Anglo-Saxon countries), there has been considerable emphasis on practical, empirical work in science classes. Reconceptualizing the teaching of science in the light of a social constructivist perspective requires, among other matters, the reconsideration of the place of students' experiments and investigations. Rather than portraying empirical work as constituting the basic procedural steps of scientific practice (the "scientific method"), it should be valued for the role it plays in providing evidence for knowledge claims. (Driver et al. 2000, p. 289)

In Mercè Izquierdo-Aymerich's work,[22] argumentation is incorporated as a central feature of her general theoretical framework for didactics of science (developed with colleagues at the Universitat Autònoma de Barcelona). She labels such framework, following Ronald Giere (1988), the 'cognitive model of school science'; this and other authors from the so-called semantic view of scientific theories in contemporary philosophy of science provide her with the conceptualisation of theoretical models that she deems to be most fruitful for science education (and hence the intersection with bridge 4).

Within this framework, school scientific arguments are cognitive and discursive tools that permit making meaningful connections between the realm of facts in the world and the models that can give meaning to those facts:

> Students reason according to their initial models, which generally have an *iconic* relationship with phenomena; a simple image may function as a model for students. Experimentation and its written reconstruction bring students to a new epistemic level, in which non-iconic (i.e., *symbolic*) signs are much more relevant. Symbols can only connect correctly with their referents if the first, more concrete step is done [...]. In order to give momentum to this process, it is necessary that students learn how to use argumentation in their discourse [...]. (Izquierdo-Aymerich and Adúriz-Bravo 2003, p. 38; emphasis in the original)

45.4 Conclusion: Towards Convergence of Argumentation with HPS

The purpose of this short conclusive section is to revisit six characterisations of school scientific argumentation with the ideas provided by an HPS-informed approach, which were discussed throughout this chapter. For each of the excerpts revisited, connections with the five bridges are made, and some HPS references (mainly from the philosophy of science) are suggested that could help in furthering the discussion only sketchily initiated here.

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[22] See Izquierdo-Aymerich (2005), Izquierdo-Aymerich and Adúriz-Bravo (2003), and Izquierdo-Aymerich and colleagues (1999).

Sampson and Clark (2008) propose to use 'the term «argument» to describe the artefacts students create to articulate and justify claims or explanations and the term «argumentation» to describe the complex process of generating these artefacts' (p. 448). This first terminological clarification reminds us of the fact that in order to fully understand school scientific argumentation, we should consider it as *a product that arises from a highly elaborate process and is therefore shaped by the very nature of that process*. Here the connection with bridge 1 is direct: an epistemic characterisation of the argumentation process is required, be it more 'internalist', focussing on inferences (e.g. Charles Sanders Peirce, Stephen Toulmin or Nancy Nersessian) or more 'externalist', looking at social interactions within the scientific communities (e.g. Thomas Kuhn, Bruno Latour or Helen Longino).

Marilar Jiménez-Aleixandre (2010) starts her book on key ideas about argumentation with a working definition of the notion; she considers it the 'ability to relate explanations and evidences' (p. 11, my translation). In this kind of phrasing, the evidence-based character of the scientific enterprise is highlighted: *evidence (in its broadest sense) becomes a key epistemic factor, one of the cornerstones of scientists' activity.* This emphasis can lead, in science education, to fruitful discussion around the notion of rationality, with questions such as what counts as 'valid' support for scientific claims, and how is this support obtained and shared? To answer such questions, related mainly to bridges 2 and 3, a postpositivistic notion of rationality can be introduced. For this kind of discussion, ideas from Stephen Toulmin,[23] William H. Newton-Smith or Ronald Giere seem appropriate.

Rosalind Driver, in one of her posthumous papers (Driver et al. 2000), advocates for a 'situated perspective', where 'argument can be seen to take place as an individual activity, through thinking and writing, or as a social activity taking place within a group – a negotiated social act within a specific community' (pp. 290–291). When arguing, *scientists give meaning to the world and communicate such meaning to peers and other audiences*; this should be a guiding idea of the nature of science discussed in the science classroom. Again, this double cognitive and social perspective can be inspected with tools from the philosophy of science and from science studies, anchoring the discussion in selected episodes from the history of science.

Anton Lawson, distinguishing himself from Toulmin's ideas on argumentation, so hegemonic in didactics of science, prefers to see

> the primary role of argumentation, not as one of convincing others of one's point of view (although that is certainly part of the story) but rather as one of discovering which of several possible explanations for a particular puzzling observation should be accepted and which should be rejected. (Lawson 2009, p. 337).

In such preference, the explanatory and theoretical aspects of argumentation are highlighted, and this might constitute a possible connection with bridge 4. Arguments *propose a way of 'seeing' the world that is structured around theoretical views*. Here, the so-called semanticist family (Giere, Frederick Suppe, Bas van

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[23] Here I refer to Toulmin (2001).

Fraassen), with their various conceptualisations of scientific theories, might prove a powerful background.

Izquierdo-Aymerich and myself accept a 'relaxation' of the requirements for an argument to be considered scientific, in tune with the naturalistic approach introduced in the fourth tension:

> An argumentation is formed by a set of reasons that convey a statement and reach a conclusion. Scientific arguments are hardly ever strictly formal (logical or mathematical); they are generally analogical, causal, hypothetico-deductive, probabilistic, abductive, inductive… One of their functions is to make a theoretical model plausible, convincingly connecting it to a growing number of phenomena. (Izquierdo-Aymerich and Adúriz-Bravo 2003, p. 38)

This approach reminds us that *there is variety and richness in the language games that have been used in science through history*. Studies around the linguistics of science, especially those following Wittgenstein's ideas, may be of use to reflect on the issues posed here.

In the last characterisation of argumentation that is reviewed for this chapter, Kuhn Berland and Reiser (2011) recover the centrality of the aim of persuasion when arguing:

> The process of attempting to persuade the scientific community of an idea reveals faults in the argument (i.e., evidence that is unexplained by the idea or misapplication of accepted scientific principles), and identifying these faults creates opportunities for the community to improve upon the ideas being discussed. (Kuhn Berland and Reiser 2011, p. 212)

It can be argued that scientific disciplines are such inasmuch as they have disciples: therefore, *it is constitutive of their very nature the will to communicate, convince, persuade and teach*. This last input for science education can find support in texts from the science studies, especially in those situated in pragmatic and rhetorical perspectives.

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Chapter 46
Historical-Investigative Approaches in Science Teaching

Peter Heering and Dietmar Höttecke

46.1 Introduction

The notion of the historical-investigative approach to science teaching was first introduced by Kipnis (1996). According to his theory, teaching and learning science within a context of history and philosophy of science (HPS) should be mastered through students' practical investigations. He suggests a middle ground between highly structured verification laboratories, which aim at generating "true" results, and open-ended experiments, where students are not guided at all. The basic idea of students doing practical work while learning science, along with its history, had been developed earlier in similar ways (e.g., Pedzisz and Wilke 1993; Rieß and Schulz 1994; Teichmann 1979, 1999).

We use the notion of the historical-investigative approach here as a broad idea that characterizes a variety of perspectives for teaching and learning science with HPS. Two central aspects are tightly joined together, the first being that science is embedded within a historical context. A central objective of this idea is to broaden students' understanding of scientific concepts and theories, to promote their interest in science, and to foster their general historical awareness. These are all ideas with a long tradition (Conant 1957; Mach 1912; Ramsauer 1953). The second aspect is concerned with the development of procedural knowledge and process skills, which are often highlighted in standard documents (Barth 2010).

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There is also a long-standing tradition in science education which calls for practical work to be done: students plan investigations, perform or even design experiments, collect and analyze data, draw conclusions, and discuss and negotiate their results. In particular, the idea of inquiry-based teaching and learning science is based on the analogy of students' activities to those of scientists. Inquiry refers to a diverse set of activities in which scientists study (e.g., Anderson 2007), explore, explain, or even manufacture (Knorr-Cetina 1981) the natural world. Scientists propose explanations based on both evidence and inference.

Several curricular standard documents, such as the NSES (National Research Council 2000), have stressed that learners should be engaged through scientifically oriented questions. They should prioritize evidence while proposing explanations which have to be critically evaluated, communicated, and justified. Inquiry learning and learning science with HPS share this special focus of student centeredness in science education. At the same time, inquiry learning and learning with and about HPS have both been shown to be useful means of learning about the nature of science (NOS). Research has indicated that NOS has to be addressed explicitly and reflectively in order to enhance the efficiency of teaching (e.g., Abd-El-Khalick and Lederman 2000; Seker and Welsh 2005).[1] Science teachers should confront students with their deeply held beliefs about science and how science works. During the last three or four decades, an extensive body of literature about NOS has been written.[2] Our analysis reveals that there are strong relationships of teaching and learning NOS and HPS on a curricular level (e.g., National Research Council 1996), with research and development in science education.[3]

Our analysis is based on two major threads of discourse: the discourse of research in HPS and the discourse of research in science education. Both are relevant to the HPSST community and for the development of ideas of how to teach science within a historical-investigative framework. In the second section of this chapter, a brief analysis of the recent discourse in HPS is presented, showing that experiments became an important focal point of historical and philosophical analysis in the early 1980s. Since then, from an epistemological point of view, experiments have no longer been reduced to a means for testing mere theoretical knowledge. The material and instrumental procedures in science are currently regarded as a central feature for explaining what science is all about, how science proceeds, and in which respect science is a cultural and human endeavor. The presentation of this

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[1] For the efficacy of inquiry-based techniques for learning about NOS, see, for example, Akerson et al. (2007), Khishfe and Abd-El-Khalick (2002), and Schwarz, Lederman, and Crawford (2004). Evidence for the efficacy of HPS for learning about NOS has been presented, for example, by Allchin (1999), Clough (2011), Galili and Hazan (2001), Howe and Rudge (2005), Irwin (2000), Kruse and Wilcox (2011), Lin and Chen (2002), and Rudge and Howe (2009).

[2] For a recent and extended overview of research on students' views on NOS, see Hodson (2009). A critical review of research methods with regard to different orientations of NOS is given by Deng et al. (2011). See also Lederman (2007), Lederman and Lederman (2012), and McComas and Almazroa (1998).

[3] See, for example, Hodson (2009), Höttecke et al. (2012), Irwin (2000), and Rudge and Howe (2009).

"experimental turn" in HPS is followed by an overview of recent research in science education regarding practical work and learning demonstrating that practical work in science education has a long-standing tradition. Central problems which have been identified by research throughout recent decades will be discussed as far as they relate to the historical-investigative approach.

Based on the analysis of these two threads of discourse, a structured discussion of several approaches in science education is presented, approaches which all have one common feature: merging the idea of teaching science with HPS with practical and investigative learning activities.

46.2 The Experimental Turn in HPS

46.2.1 Investigating Science as Practice and Culture

Understanding science as a cultural activity gained increasing importance during the second half of the twentieth century. Such a view breaks with positivistic accounts, which describe the development of science and scientific knowledge as progressing towards the truth, and allows a description of science as something that is shaped or even influenced by factors which might have been regarded as nonscientific. Such a cultural perspective is closely related to a constructivist understanding of science. A number of studies aim at describing and understanding science as a sociocultural practice. Among them are laboratory studies (Knorr-Cetina 1981; Latour and Woolgar 1979), as well as social science studies (e.g., Shapin 1994). The analysis of science under a sociocultural perspective has shown, in particular, different ways in which a scientific consensus might be reached and the role that social factors, such as authority and reputation, might play in the establishment of scientific knowledge (e.g., Collins 1985; Galison 1987).

Besides social and cultural aspects of science, the role of material objects, such as scientific instruments and material procedures, received scant attention by those studying the history and philosophy of science until about 1980. Since then, they have become increasingly important for the development of a comprehensive understanding of science as a process. For decades, instruments and their use, development, and history had been an issue only for a small community of historians of scientific instruments. The recognition of material and instrumental procedures in science has been a more recent development in HPS. Accordingly, laboratory notebooks have become an important source for detailed accounts of scientific practice at the workbench.[4] The consideration and analysis of science as a visual practice is

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[4] For discussions of laboratory notes, see, in particular, Holmes et al. (2003). See also Steinle's studies on Faraday (Steinle 1996) and Dufay (Steinle 2006). For further case studies based on Faraday's laboratory diaries, see Gooding (1990), Tweney (1985), and Höttecke (2001).

another recent tendency in HPS. Images and their role in shaping and communicating scientific ideas and results have, therefore, been analyzed in detail.[5]

Even though instruments and instrument collections have been a topic of research for quite some time, there are some recent developments in this field which deserve a closer look. Traditionally, research on scientific instruments had two major directions of impact: either there was a scope on the construction of particular instruments, since they were regarded as highly relevant to the general development of science (e.g., development of theories, confirmation of laws, instrumental procedures), or instrument collections were analyzed in order to explore and characterize distinguishing features they had in common (e.g., collections of microscopes). Accounts on the history of scientific instruments that followed one of these two research traditions remained, by and large, descriptive. The material and procedural aspects were scarcely considered to be an important issue.

Besides these two approaches, there were a few early studies which focused on experimental practices in science, probably the first one being Settle's experimental analysis of Galileo's inclined plane experiment (Settle 1961). The methodological approach that he used was particularly innovative: he reenacted the experiment with a reconstructed device. Several similar studies followed which also analyzed experiments described by Galileo (Drake 1970; MacLachlan 1973). The experimental approach, while being limited to experiments that had been described by Galileo, can be understood when the aim and context of the experimental analysis are taken into consideration. During the 1960s and 1970s, Galileo's experimental accounts were regarded as fictitious. Historians and philosophers of science held the notion that Galileo, being predominantly a theoretician, used accounts of experiments merely as devices to strengthen and clarify his theoretical arguments. It was doubted that Galileo had ever carried out the experiments he described in his publications. Consequently, the reenactments were intended to demonstrate that Galileo had, in fact, been able to carry out these experiments according to his description.[6]

Since the early 1980s, experimentation in science has received more attention than ever before from historians and philosophers of science.[7] Initially, history of science was concerned foremost with the development of theories. According to this view, the only role experiments could ever play in science was limited to confirming theories or even just providing the possibility of falsification (Popper 1934). During the early 1980s, some studies, however, began to focus on experimentation as an independent aspect of the formation of scientific knowledge, alongside the development of theoretical knowledge. In this respect, Ian Hacking's

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[5] For a discussion on the role of images in the sciences, see, in particular, Heßler (2006) and Busch (2008). For discussions of images and their role in nanotechnology, see Bigg and Hennig (2009).

[6] There are, of course, some earlier examples which analyze materials, as well as practices, through reenactment. The field in which this method was likely first applied is archeology, the most prominent example being the demonstration by the Norwegian Thor Heyerdahl, in the late 1940s, of the possibility of travelling from the American Pacific coast to Polynesia with a simple raft.

[7] See, for example, Collins (1985), Galison (1987), Gooding (1990), Gooding and James (1985), Gooding et al. (1989a), Hacking (1983), Radder (2003), Schaffer (1983), and Shapin and Schaffer (1985).

dictum that "experimentation has a life of its own" (1983, p. 150) became well known. Experiments were regarded as a central element in the process of knowledge production. Manipulations of the natural world have multiple facets and cannot be used merely to test assumptions.

Such a wide view of experimentation also contributed to a new awareness of instruments in the history of science. Instruments were, at the time, considered to be artifacts which were designed and constructed according to explicit objectives, their function and shape possibly even having changed over the course of their use. They could not be taken for granted as objects anymore, as they were believed to have been a crucial part of experimental and manipulative practices of the past. Their meanings were not regarded as anything established or given anymore but as developed in laboratories and elsewhere as a result of material, social, and cultural practices. Hence, their materiality and contingent use were seen as relevant objects of historical science research.

The general experimental or even material turn in HPS described above also led to new perspectives for science museums. Historians of science criticized the restoration of a historical instrument as a mere transformation into a mint condition. During the process of restoring an old instrument, traces of its former use should be kept rather than displaying it as a cleanly polished instrument. Historical analysis focused on such traces because they were regarded as signs of the historic progression of an instrumental procedure. Instrumental procedures were not regarded as unproblematic, stable, or even fixed but as probably changing over the course of the development of an experiment.

46.2.2 Investigating Material Procedures

The experimental turn has not resulted in a diversified research focus. Various different directions and research currents can instead be identified. Research focusing on the historical analysis of scientific experimentation either emphasized the material or the methodological character of experiments. The latter idea can be "found in studies that understood science in terms of activity rather than contemplation. Science was to be understood not as a body of knowledge but as a network of embodied practices" (Morus 2010, p. 775). Such a historical perspective is related to a broader understanding of the role of experiments in knowledge production: "The aim of the experimenter is to transform … inscriptions to a stage where they seem capable of but one reading and become powerful weapons in argument" (Gooding et al. 1989b, p. 5).

A central approach can be seen in various attempts to analyze historical experiments by the method of replication. This approach follows a tradition founded by the studies of Settle, Drake, and others regarding Galileo's work, already mentioned above. The general focus of the historical investigations of experimental practice, however, shifted from a mere reproduction of experimental results presented in original papers towards detailed accounts of experimentation as both process and practice. Material manipulations, instrumental procedures, and their general relationship to the development of theories or models were under scrutiny. Yet, it has to be noted that even in his first paper, Settle had already made another aspect explicit: "To get a better appreciation for some of the problems he [Galileo, P.H.] faced I have tried to reproduce the experiment essentially as Galileo described it" (Settle 1961, p. 19). Settle's point is remarkable for his time. He identifies a central aspect of this kind of research: the idea is not to question the experimental findings but to develop an understanding of the crucial details of the experiment and the difficulties that Galileo might have had to face due, in part, to choosing adequate materials and instrumental design and to developing the respective skills that are required for a successful performance.

One of the first researchers to apply this methodology more systematically was David Gooding, who analyzed experiments described by Michael Faraday. While doing this, Gooding developed a particular focus:

> [S]ince skills cannot be recovered from the familiar literary and material forms of evidence - manuscripts, publications and instruments - historians of science should, if possible, venture beyond these, to study the activity that produced them. … Empirical results never are entirely independent of the practices that let to their production. Facts are practice-laden as well as theory-laden. … If much of what experimentalists do cannot be recorded, it cannot be recovered by reading texts or even by studying apparatus (Gooding 1989, pp. 63 f).

Besides Gooding, it was the Oldenburg group, in particular, established by Falk Rieß, which systematically developed the methodology of reenacting experiments of the past. Their so-called replication method[8] was based on the reconstruction of an apparatus as close as possible to the available historical evidence, which might be presented in written sources or even surviving instruments. Such reconstructions were used for authentically reconstructing material procedures and instrumental manipulations. The major objective was to write case studies about reconstructed and analyzed scientific practices. This replication method has been established during the last two and a half decades. Meanwhile, other researchers apply this (or an adapted) methodology, which is particularly prominent in the physical sciences.[9] There are also examples of it being used in chemistry[10] and some in biology.[11]

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[8] For systematic discussions of the method, see, in particular, Breidbach et al. (2010), Heering (1998), Rieß (1998), and Sichau (2002). For a slightly different methodological interpretation, see Frercks (2001). Case studies are collected in Breidbach et al. (2010) or Heering et al. (2000). Moreover, see for single cases Engels (2006), Heering (1992, 1994, 2002, 2005, 2006, 2007, 2008, 2010), Heering and Osewold (2005), Hennig (2003), Höttecke (2000, 2001), Kärn (2002), Müller (2004), Sibum (1995, 1998), Sichau (2000a), Staubermann (2007), Voskuhl (1997), and Wittje (1996).

[9] See, for example, Cavicchi (2006), Fiorentini (2005), Lacki and Karim (2005), Martínez (2006), Palmieri (2008, 2009), and Staubermann (2011). The Jena group, led by Breidbach, focuses more strongly on the reconstruction of the instrument than on the practice with the instruments. For a detailed account, see Breidbach et al. (2010), as well as Frercks and Weber (2006).

[10] See, for example, Fatet (2005), Principe (2000), Tweney (2005), Usselman et al. (2005), Chang (2011), and Eggen et al. (2012).

[11] See, for example, Maienschein (1999) and Maienschein et al. (2008).

Moreover, the approach is no longer limited to the history of science; it has also gained importance in other professional fields, most notably in technology[12] and cultural studies.[13]

Manual procedures are usually hard to communicate, and complex manual procedures cannot be explicitly communicated at all because of their tacit nature (Collins 1985; Polanyi 1966). One may think, for instance, on how hard or even impossible it is to explain exactly how to ride a bike without tumbling. Detailed accounts on laboratory practice, including their tacit dimensions, require new methods. The replication method, however, allows for an analysis of the complex interactions of materials, instruments, rooms and spaces, people, their bodies, and the associated theoretical ideas. Additionally, the analysis comprises an account of the social and cultural meanings to which an experiment or instrument may be related, such as norms and values in science and beyond.

In summary, history and philosophy of science have embraced scientific experiments and instruments, as well as practical manipulations of scientists, in a new way during the last three decades. As a result, our current understanding of their role in the production of scientific knowledge and the establishment of scientific practices has increased. As we will show in Sect. 46.4, the role of experiments, instruments, and practical manipulations corresponds to recent developments in HPS-informed science education. The next step is to recapitulate briefly what we know about practical work in science education in general.

46.3 Research About Practical Work in Science Education: A Background for Historical-Investigative Approaches

Experiments and practical work are of great importance in science education. Scholars have long argued in favor of its predominant role. For natural studies, practical fieldwork became important in the USA towards the end of the nineteenth century (Kohlstedt 2010). In physics, practical work became an accepted part of high-school education in the USA by 1910 (Rosen 1954).[14] A commission of the German Society of Natural and Medical scientists released a document with recommendations (GDNÄ 1905 according to Willer 1990) in the early twentieth century. More than a 100 years ago, scholars had already emphasized the importance of practical work in science education for the enhancement of process skills, as well as for general attitudes of accuracy and exact observation. The commission emphasized that science should be taught as an exemplar of how knowledge is generally

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[12] One of the best-known examples in this field is Wright's analysis of the Antikythera mechanism (Wright 2007); for other examples, see the contributions in Staubermann (2011).

[13] Most prominent is the discussion on the role that the camera obscura may have played in painting. For a summary of the discussion, see Lefèvre (2007).

[14] For the process of transition from textbook to practical work, see, for example, Hoffmann (2011), Kremer (2011), and Turner (2011).

acquired in the empirical sciences. While the first idea is still accepted today, the idea of a clear-cut, single epistemic methodology appears to be obsolete.[15] This does not mean that science is not driven by a limited number of methodological rules, like, for instance, the use of controlled experiments or avoiding ad hoc revisions to theories (Irzik and Nola 2011).

Even today, there is wide agreement among science educators that practical work is of general and great importance for teaching and learning science. A European Delphi study, for instance (Welzel et al. 1998), gathered empirical data on the main teaching objectives for laboratory work in science education, as recognized by science teachers at the upper-secondary and first-year university level. According to this study, the great value of experiments and laboratory courses is seen as important for reaching several educational objectives. Through them, students can learn how to connect theory and practice in science and how to test knowledge. There are opportunities for the enhancement of process and social skills, scientific thinking skills, motivation, and personality development. Besides the general appreciation of practical work in science education, the teachers in this study valued structured and guided instructions of students' laboratory activities, which were seen to be of high importance for the development of experimental skills and insights into the relationship between theory and practice.

Recent research in the history of science that focuses on experimentation has strongly stressed the idea that scientific experimentation is a multifaceted activity with many possible relationships between experimentation and observation, on the one hand, and inference and theory development, on the other (e.g., Hacking 1983; Heidelberger and Steinle 1998). The Kantian idea of an experiment where a scientist directs questions to nature like a judge to a witness can no longer be supported, since nature cannot be regarded as an unaffected and independent agency (Kutschmann 1994). According to our current understanding, a scientific experiment is, instead, an act of intervention, where questions, interests, public and private perspectives, background knowledge and skills, an experimenter's body, instruments, rooms and spaces, material and theoretical entities, and procedures interact to develop science within a cultural and societal context (see Sect. 46.2 of this paper).

The actual role and use of experiments in science education presents a somewhat problematic situation. An extended video-based study focusing on physics education in Germany has shown that experiments usually play a major role in physics teaching (Tesch and Duit 2004); however, teachers appreciate the role of experiments in science teaching only in a rather general way. Jonas-Ahrend (2004), reporting her findings from an interview study with physics teachers, asserts that the educational purpose and relationship between students' experimentation and their learning are hardly considered by teachers. Strong guidance of lab activities in science education has often been criticized as cookbook-style[16] or even as a verification laboratory (Kang and Wallace 2005; Metz et al. 2007) because it fosters a

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[15] See, for example, Feyerabend (1972), Hentschel (1998), Pickering (1995), and Ziman (2000).

[16] See, for example, Clough (2006), Hofstein and Kind (2012), Hofstein and Lunetta (2004), and Metz and Stinner (2006).

portrayal of science as a rhetoric of conclusions or even indoctrinates students in correct procedures (Nott and Wellington 1996). Inquiry or "discovery" learning may pose the danger of misrepresenting science as primarily an inductive endeavor. According to Harris and Taylor (1983), a pure inductivist idea of science may bear several pedagogical pitfalls. They consider the problem that in following an inductive perspective on science, a certain chain of inferences from observations to conclusions rules out alternative explanations of phenomena. They criticize the lack of a coherent philosophy of science implicit in curricular material. Science, if outlined as inductive, might even justify an alleged "progressive" view on education, according to which the child is misleadingly regarded as autonomous and experiences practical work as authentic.

It often happens that students do not really know what the purpose of an experimental procedure they follow or the meaning of the data they collect might be.[17] According to Gallagher and Tobin (1987), high-school teachers rarely consider whether their students really understand what they are doing and what their experimental results might indicate. Science teachers hardly exhibit behavior that encourages students to think about the nature of scientific inquiry in a reflective manner. Thus, it is hardly surprising that research has indicated that students have a limited understanding of the nature and purposes of experimentation in science.[18] Concerning the current situation in science teaching, Hofstein and Kind (2012, p. 192) have concluded that "practical work meant manipulating equipment and materials, but not ideas."

Whenever students perform experiments, neither their ideas nor their performances resemble what scientists in their laboratories are actually doing. Chinn and Malhotra (2002) have compared students performing so-called "simple" experiments with scientists doing authentic inquiry. They conclude that the cognitive operations of both are rather different. While scientists generate their own questions, questions are often directed to students. Students usually investigate only one given variable, while scientists have to select or even invent variables to investigate. Students are usually told what and how to measure; scientists, however, incorporate multiple measures of independent, intermediate, and dependent variables. Whereas students usually draw conclusions from a single experiment, scientists coordinate results from multiple studies. Such differences reveal the deep gap between regular inquiry activities at school and the ways scientists perform their experiments.

This gap is also mirrored in teacher students' understanding of experiments. In a study based on focus group interviews, Gyllenpalm and Wickmam (2011) found out that Swedish university teacher students understand the notion experiment rather as a method of teaching than a method of scientific inquiry. According to this study an "'experiment' was never explicitly associated with a particular methodology for producing new knowledge about causal relationships" (ibd., p. 920) and rather used

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[17] See, for example, Flick (2000), Hart et al. (2000), Hofstein and Kind (2012), Hofstein and Lunetta (2004), Lunetta et al. (2007), and Schauble et al. (1995).

[18] See, for example, Carey et al. (1989), Lubben and Millar (1996), Meyer and Carlisle (1996), Milne and Taylor (1995), and Solomon et al. (1996).

in an everyday sense of the word. As long as science education lays claim to the idea that the practical work of students and experiments in science should have anything in common, there is a bridge to be built between different views of experiments in science and in science education.

Scholars have stressed the role of open-ended activities within an inquiry framework, which has been shown to be superior to strongly guided practical work (e.g., Berg et al. 2003). Trumper (2003) demands that from a constructivist perspective of teaching and learning, the way that we teach in the laboratory should be rethought. Anderson (2007) summarizes the features of a new student orientation towards a becoming more self-directed learner. Under such an orientation, students process information, as well as interpret and explain data. They design their own activities, form interpretations of data, and share authority for answers. Still, inquiry learning should not be unguided since research from the field of educational psychology (Kirschner et al. 2006) warns us that the advantage of guidance begins to recede only if learners already possess sufficient prior knowledge to cope with a certain problem. Researchers have generally emphasized that science teachers should focus on a stronger process perspective, instead of the restricted perspective of scientific content (Flick 2000). Practical work in science education should aim towards an understanding of scientific evidence (Gott and Duggan 1996). The general role of metacognitive activities (Hofstein and Lunetta 2004) should be more greatly appreciated. The same holds for the teacher's supportive role in cognitive scaffolding – the interactive instructional strategy where teachers provide tailored instructions based on a diagnosis of the abilities and problems of their students.[19]

Several educational consequences follow from the view of science as a social endeavor. Scientific inquiry appears to be an activity where one makes sense of material and empirical and theoretical entities which have to be presented to a community of experts. Problems of validity cannot be solved by a single scientist in his or her laboratory. Instead, communities of peers have to criticize, negotiate, debate, and even revise the meaning and prevalence of any entity in science. Such a sociocultural view of science accompanies a Vygotskian perspective (Vygotsky 1978) of teaching and learning, one that stresses the social context of cognitive development. Students interact with each other and build communities of practice in order to promote learning. Accordingly, Duschl (2000) calls for instructional sequences in science teaching and learning to be more strongly oriented to the epistemic practices of science. Discussions, debates, and arguments about what counts as evidence deserve a more prominent role in teaching and learning.

Several approaches in science education, and especially in the field of history and philosophy of science in science teaching (HPSST), have been developed throughout recent decades. They continue the general appreciation of student-centered laboratory courses, open-ended inquiry activities, and manipulative investigations of material objects within a context of HPS. In the following section, the character and role of such approaches are analyzed and discussed.

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[19] See, for example, Flick (2000), Valk and Jong (2009), and van de Pol et al. (2010). Tao (2003) explicitly calls for actively scaffolding students' understanding while using science stories about NOS.

46.4 Historical-Investigative Approaches in Science Education

There are several approaches to teaching and learning science which are closely related to the historical-investigative approach. Each of them stresses different aspects of teaching, learning, students' activities, experimentation, scientific instruments, or HPS in general. For each of these approaches, we will discuss the role played by HPS, on the one hand, and the role of students' investigative activities, on the other. To illustrate both extremes, some approaches strongly focus on investigative activities or inquiry-orientated learning, which is inspired only by scientific experiments of the past. Other approaches stress the role of historical context in teaching and learning science, while students' own investigations are clearly instructed by historical patterns.

In brief, historical-investigative approaches in science teaching are characterized by balancing the following aspects or a combination of them in a particular way:

- Contextualizing science with its history and philosophy
- Stressing material, social and/or cultural aspects of science
- Enabling teaching and learning about NOS
- Allowing for students' more or less guided own practical explorations of natural or technical phenomena
- Basing students' investigations on research activities related to past science
- Enabling students' critical reflections of their own actions and learning, as well as fostering their reasoning skills
- Using aspects of HPS to allow students to deduce their own meaning of their experiences with material entities and their manipulations and vice versa

In the following section, several approaches will be discussed which essentially fit into the general category of historical-investigative teaching and learning. We are aware that the authors of the work presented below might consciously have avoided the notion "historical-investigative" as an accurate account of their own work. Nevertheless, since we want to discuss the breadth of connate approaches in different educational fields without neglecting fundamental differences, we have decided on subsuming all these approaches under this common topic.

Besides the conceptual differences which will arise in the discussion below, one has to remember that science teachers favoring or rejecting a certain approach usually depend on the availability of resources and not necessarily on conceptual considerations.

46.4.1 Historical Investigations Within a Narrative Approach

Recently, stories have received more attention from educators favoring a historical approach. While most of the respective case studies clearly distinguish between a historical narration and an (independent) inquiry with modern materials, there are also a few exceptions that can be seen as a historical inquiry approach.

An example of such an approach has been developed by Metz and Stinner (2006), who have adapted the replication method. The general structure of the activities is retained, but while the replication method emphasizes a reconstruction of instruments, materials, and procedures as close to the available sources as possible, Metz and Stinner argue for a method called "historical representation." Historical representations are specific forms of case studies which recommend the reproduction of historical experiments with modern materials. A central idea is that students interact with a narrative about the history of science through the experiments they are performing. The activities they design and perform alternate between their own ideas and prior knowledge and those presented by the narrative. This means that students formulate hypotheses on their own, design tests, and, finally, compare and contrast their own ideas, experiences, and measurements with the original work. Explorations performed independently from the original are, therefore, welcomed. The use of alternative materials and innovative adaptations of the original instruments, materials, or procedures is encouraged. The experiments the students perform are not intended as verification labs but as a means to address the nature of science explicitly. The historically based investigation comprises four parts or phases: introduction, experimental design, experimental results, and analysis and interpretation of data and explanation.

Narrative approaches are, however, not without any danger. Metz and his colleagues (2007) mention that "we cannot expect students on their own to develop a critical stance towards narrative; thus mediation to guide students through a process of critical analysis should be an essential component of the narrative process" (Metz et al. 2007, p. 320). Accordingly, Tao (2003), in a study with 150 secondary-school students, found that science stories are useful contexts for students to argue for their preexisting views on NOS. As a consequence, the teacher should actively scaffold students' understandings in order to support students' cognitive development.[20]

The strategy of redoing scientific experiments of the past is also employed by Chang (2011). Here, history of science serves as a source for the exploration of peculiar and supposedly well-known natural phenomenon, which concerns accounts about how knowledge in science not only is generated but also forgotten. He demonstrates that a seemingly clear scientific "fact," such as the boiling point of water, becomes questionable or even obscured but may be demystified in the light of evidence of science from the past. Chang recovers past scientific knowledge, which has been forgotten instead of being integrated into the body of accepted knowledge we call current science. He shows that the boiling temperature of water notably depends on the form of the vessel in which the water is heated. He considers that "[g]etting involved in historical experiments will almost invariably teach students (and teachers) that things are more complicated that they had been led to be believe" (Chang 2011, p. 322). As a result, the experimental difficulties of a historical situation can serve as a basis for inquiry-based activities that focus on the peculiarities of the boiling temperature of water, yet, even without necessarily referring explicitly to the historical context.

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[20] See footnote 19.

A thoughtful consideration of past science helps students to realize that modern science deals with a restricted range of objects, methods, and materials. Likewise, Vera and his colleagues (2011) describe a "simple experiment with a long history," the combustion of a candle in an inverted vessel that is partly immersed in water. This experiment was initially described by Lavoisier, though it can be traced back to antiquity. Similar to Chang's examples, they demonstrate the historical development of a classical experiment and expose potential difficulties that may have played a role in the historical discourse, as well as in generating a misconception about the explanation that can be found even in fairly recent textbooks. Yet, the methodological approach of Vera et al. is somewhat different in that it also involves computer simulations in communicating their experiments.

Experimental approaches of elementary-level scientific content immersed in a historical context appear to be a straightforward and unproblematic variation of a historical-investigative approach. Yet, there are some problems with respect to the historical context that, on first sight, appears to be clear and evident. A good illustration in this respect is Kipnis' discussion of Oersted's experiment on electromagnetic interaction (Kipnis 2005). He argues that Oersted's discovery of electromagnetism is an example of the role chance might play in the development of scientific knowledge. Even though Oersted's experiment is frequently described as being based on chance, this perception might be caused by a lack of an adequate consideration for the Romantic movement in physics and its role in theory development. Martins (1999), for example, argues strongly that Oersted's work has been based on theoretical considerations influenced by Romantic natural philosophy.

46.4.2 Historical Investigations Starting from Laboratory Diaries

Original manuscripts and, in particular, laboratory notes can provide an authentic basis for structuring a conceptual and procedural understanding of science. The collection of Michael Faraday (1932–1936) is a prominent example of such manuscripts due to the extensive detail and the availability of his notes and even more so because his laboratory diary was published in the 1930s. Crawford (1993), as well as Barth (2000), uses different sections of Faraday's notebooks in their classroom as a starting point for students' investigative activities. According to Crawford, there are at least three aspects that turned out to be beneficial: "In fact, some of them [Faraday's problems] were problems the pupils shared, but said that they had previously felt stupid about declaring their puzzlement" (Crawford 1993, p. 205). When following Faraday's problems, however, Crawford "had shaken their faith that someone somewhere, at least in teaching/learning situations, would eventually produce an answer. They had to think for themselves" (Crawford 1993, p. 205). The students did not only develop a conceptual understanding from these lessons but "they also learnt and recognized for themselves many things about science itself" (Crawford 1993, p. 205). Faraday's experimental accounts were used as a kind of "starter" (Crawford 1993, p. 206) of students' own inquiry-based activities.

Likewise, Barth (2000) used Faraday's laboratory diary to enhance students' understanding of electromagnetic induction. Suitable chapters from Faraday's notebook were presented to the students as a basis for their own inquiry activities on electromagnetic induction. Following Faraday's notes, the students made their own discoveries about electromagnetic induction using modern equipment while guided by Faraday's original experimental ideas. Moving back and forth between the diary and the apparatuses – reconstructions of an experimental apparatus and a modern version – the students were able to develop their own understanding. Moreover, they experienced the difficulties of stabilizing and amplifying an effect adequately, difficulties comparable to those that Faraday and his contemporaries faced. It is remarkable that Barth even managed to guide his students to the point where they developed insight into an initial mistake that Faraday had made. Faraday, in a letter to his friend, Philipps, discussed the directions of an electric current induced by a primary current in a parallel wire but then predicted the wrong directions of electromagnetically induced currents. While Faraday, himself, corrected his mistake a short time later in his official paper to the Royal Society, his initial incorrect prediction of an electric current has only been recognized by a few science historians (Romo and Doncel 1993).

46.4.3 Historical Investigations and Instruments from Past Science

Experimenting with historical or reconstructed instruments opens up new ways of understanding science as an experimental practice. Reconstructed historical devices, as well as original apparatuses, can be used in formal and informal science education. A leading approach in this respect has been recognized by Devons and Hartmann, who developed a "laboratory devoted to repeating crucial experiments in the history of physics with apparatus reconstructed according to the original descriptions" (Hartmann Hoddeson 1971, p. 924). One of the criteria they use is similar to the ones claimed in historical studies based on the replication method. According to them, "methods and materials used in these experiments are essentially those used originally" (Devons and Hartmann 1970, p. 44). Their work[21] serves as a starting point for several followers who reenacted historical experiments for educational purposes. Among the major objectives are both an enhanced understanding of experimental practice with a special focus on reconstructions of material and performative aspects of science. The approach is particularly motivated by the general objective that learners should thoroughly understand how knowledge in science is generated or even manufactured (see, e.g., Heering 2000, 2007; Höttecke 2000, 2001; Kipnis 1993; Rieß et al. 2006). Experiments do not appear to be simple devices for answering questions in a yes-or-no manner but allow for detailed accounts on how instrumental and material manipulations in science interact with theoretical and cultural entities.

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[21] See also Devons and Hartmann Hoddeson (1970) and Hartmann Hoddeson (1971).

Reenacting historical experiments is an approach that has been systematically used by the Oldenburg group, led by F. Rieß for research in HPS (see the Sect. 46.2) and for educational purposes. The method was mainly used in physics teacher-training courses[22] although there are also some instances where this approach has been used at a secondary-school level (Heering 2000; Höttecke et al. 2012). This approach is based on replicas which were largely developed in the process of analyzing historical experiments with the replication method. Replicas of historical instruments are often characterized by material cultures of a certain time and space. Materials favored by natural philosophers of the eighteenth century, for instance, were amber, natural resin, shellac, or glass, but not PVC. Replicas, therefore, allow for new experiences with materials and their possibly peculiar qualities, with which students are often unfamiliar. Thus, this approach aims to explore the material culture of a particular time. Moreover, replicas are usually not designed for teaching purposes but originate from authentic laboratory practices of the past. Replicas still represent theoretical ideas which are embodied in instruments, materials, and the ways that they were used at the workbench. Hence, they are a rich resource for investigating the distinctive interaction between material and theoretical entities, as well as between instrumental and social practices in science. An important feature of this approach generally is that knowledge, data, and the experiences of the students working with the replicas are not isolated. The Oldenburg group used them as a rich resource for contextualizing experiments, materials, and instruments from specific cultural and societal perspectives.

During the past three decades, a rich resource of replicas, mainly from the history of physics, has been constructed. The STeT project (Science Teacher e-Training) has been looking for new ways to provide teachers with materials connected to the history of instruments and experiments (Kokkotas and Bevilacqua 2009). Among the materials are short films, which demonstrate how the replicas work in action. The project HIPST (History and Philosophy in Science Teaching) uses the idea of developing case studies. Some of the cases developed in HIPST enable teaching and learning about science and NOS with an explicit focus on students' historical investigations with replicas. A wide range of student-centered activities and materials have been developed for teaching and learning, including role-play, films, and methods for explicitly reflecting the NOS (Höttecke et al. 2012).

46.4.4 Historical Investigations with Modern Materials

Several approaches use the working principle of historical experiments for educational purposes without using replicas, historic materials, or even original instruments. For these approaches, historical context still becomes the focal point around

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[22] See, for example, Rieß (2000), also Sichau (2000b) on thermodynamics and Höttecke (2000) on electricity.

which teaching and learning must be organized. Such approaches[23] can, therefore, be seen as modifications of those discussed in the former section.

Tsagliotis (2010) has developed a case study where primary-school students construct microscopes with modern materials, such as PVC tubes and plastic lenses. They make observations and relate them to simplified chapters of Robert Hook's *Micrographia*. Maiseyenka and her colleagues (2010) show how the historical context of cooling and ice production may be enhanced by students' own investigation of physical principles, such as the effect of the dilution of salt on evaporation or on freezing mixture. The case study is addressed with students in grades five to seven where the topic of producing and enjoying ice cream is of interest.

According to Kipnis' (1996, 2002) idea of historical-investigative teaching, science students would rather imitate scientists than use artificial or contrived experiments found in regular science education. He suggests that several modifications should be allowed to be made to the original experiments. Thus, using such an approach means that students begin their own investigations from a historical context rather than reenacting an experiment. Kipnis stresses that through this approach, students have the chance to become discoverers. Students should realize that they are capable of repeating certain important steps of famous scientists on their own. This approach enables students' decision-making regarding the proper result of historic scientific disputes. Building their self-confidence is another important expected outcome. Furthermore, students should appreciate the great discoveries of the past and learn about the strategic elements of experimenting. On the other hand, Kipnis suggests quite a strict structure for integrating experiments into historic contexts. According to his strategy, during an investigation, students formulate a problem based on a specific historical background. Then, they must identify and select relevant variables. All variables should be examined independently in order to test a hypothesis. Finally, the students must draw general conclusions based on their analysis of the variables and their effect on a certain phenomenon. While the students learn how to control variables in a clear-cut way, many aspects of scientific experimentation discussed in Sect. 46.2 are in danger of not being adequately considered. The step-by-step method aimed at "producing true results" (1996, p. 281), combined with the act of restricting experimentation to the examination of variables and test of hypotheses, hardly matches the constructive role of practical manipulations, material procedures, or explorative strategies of experimentation in science. This is not surprising since Kipnis stresses science as a "drama of ideas" (1996, p. 288).

Allchin (1999) describes an introductory science lab course for nonscience majors using history of science as a curricular guide. Within the year-long interdisciplinary course, outside the regular curricular teaching structure, instructors enjoyed significant freedom. The designed "historically inspired labs" focused, among others, on topics like basic astronomy, early medicine, density of matter, Galileo's ideas on pendulum motion, production of paint, electrophysiology, titration of vinegar, and the ballistic pendulum. Most instruments were adapted from existing introductory laboratory course materials. The instruments, even though

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[23] See, for example, Achilles (1996), Kipnis (1993, 1996, 2002), Teichmann (1979), Teichmann et al. (1990), and Wilke (1988).

modern, were "set more explicitly in their historical context and with added emphasis on reflecting the investigatory process" (Allchin 1999, p. 620). The main objective of the course was "a coupled understanding of the content and process of science" (Allchin 1999, p. 621). Therefore, the investigatory activities were related to real science in a wider sense; for example, during a lecture, an instructor demonstrated the hydrostatic paradox, which means that the hydrostatic pressure of a water column only depends on the depth of the column and not on the shape or the volume of a vessel. After the demonstration, the students started to suggest a variety of different tubes in order to explore their effect on pressure.

While all approaches discussed in this section start with a historical context from the very start of teaching, Allchin (1999) mentions an alternative option. According to him, history of science has often been introduced retrospectively as a way of reviewing the students' investigations, their experiences, and results. Thus, history of science was not directly related to students' investigations from the outset but used as a means for reflecting experiences with instruments, experiments, and phenomena retroactively. Nevertheless, as the students indicated, the labs were integral for understanding how science works.

Lin and colleagues (2002) present evidence of the effectiveness of a teaching approach based on practical activities of students in an HPS context. They conducted a 1-year study, with grade eight students, about the efficacy of promoting students' problem-solving ability through history of science teaching. A treatment group was compared to a control group. The students were randomly assigned to one of the groups. The treatment group was taught with an emphasis on the development of scientific content. Students learned details about how previous scientists discussed, debated, and hypothesized and how they conducted experiments. Either teacher demonstrations or students' hands-on activities were analogous to the experiments and ideas of previous scientists. The students simulated historic experiments and were required to predict their results. They formulated hypotheses, explained their own reasoning, and reflected on analogies and differences between their own hands-on activities and those of previous scientists. The control group was taught in a somewhat traditional manner. There, students worked according to cookbook-style labs, aiming at getting correct answers. They had to follow predetermined procedures, listen to lectures, and solve problems presented in textbooks. Statistical analysis of pre- and posttest data indicated significant effects of the treatment regarding the problem-solving abilities of the students. Unfortunately, there is still a lack of empirical evidence about the efficacy of the practical work of students framed by the history of science. The results of this study are, nevertheless, encouraging.

46.4.5 Historical Investigations in Science Museums and Instrument Collections

Original historical instruments are rarely used in science education. A reason for this is probably their status of having historical and heritage significance. Therefore, they have to be preserved and saved from any damage. There are, however, a few examples where instruments have been used in reenacting historical experiments in science education, most notably an experiment on the decomposition of water, performed in a history of science course at the university level (Eggen et al. 2012). Here, part of the apparatus for decomposing water was borrowed from the historical teaching collection, while the voltaic pile was reconstructed according to descriptions from 1800. The authors concluded that the exercise enabled valuable insight, both into the nature of the devices they had used and the experiment as a whole. Likewise, original microscopes and telescopes are used in science museums for educational purposes. There, they illustrate the optical quality, as well as the magnification, of these devices.

Cavicchi (2008) describes the visit of a group of students with a disparate background in science education to the MIT Museum's collection of historical telephones. The students explored several historic devices, such as telephones and a nineteenth-century Voltaic pile. They even "had to innovate distinctive actions such as unscrewing a lid, releasing a crank, picking a lock" (Cavicchi 2008, p. 726) in order to surmise the workings of the telephones in relation to their construction and materiality. Lissajous figures were produced by reflecting light off orthogonal nineteenth-century tuning forks. Students' investigations were enriched through the use of historic texts. The main focus of the approach is to enable intensive experiences with physical phenomena while exploring the historical context of their emergence. Cavicchi calls her approach "critical exploration," according to earlier work from cognitive psychology. As the undergraduate students engage with complex phenomena and materials, they experience, firsthand, the relationship among the critical components: the materials, their own actions, and history. The students' actions put them in the shoes of past historical investigators who had also developed an understanding of science through experimentation with materials.

Reconstructions of past experimental instruments have also entered museums. In those cases, they might be placed close to the original items in an exhibition. Visitors are allowed to use them instead of the original devices. In this way, a similar experience as would be had with the original device can be achieved without threatening the museum curator's responsibility to preserve the heritage of the device (Heering and Müller 2002). An alternative might be to offer visitors the opportunity to reconstruct instruments on their own in a simple manner. Such a procedure is based on historical artifacts (or their reconstructions) and thus enables new insight into the material culture of scientific experimentation (Heering and Sauer 2012).

Barbacci and her colleagues (2010) present a case study called "Discovery of Dynamic Electricity and the Transformation of Distance Communications," which is designed as an informal educational activity. It is addressed to high-school students and teachers and aims to bring out interrelations between history of science and general social history. The case study has been developed and tested in the Fondazione Scienza e Tecnica's physics laboratory collection in Florence, Italy. During an interactive workshop at the Fondazione, it is possible to explore several of the central topics in electrodynamics from a historical perspective, like the invention of the galvanic battery, the use of electromagnetic coils, and the early application of the galvanoscope, galvanometer, and electromagnet. The lesson moves on to the invention of the telegraph, which is placed into a context of the development of railways, the problem of establishing standard time, and submarine telegraphy, and the sociocultural implications of these phenomena. The lesson presented at the museum follows a narrative-experimental approach: historical background information is presented together with certain scientific discoveries and their technical applications. Experiments and instruments matter on two levels, as a hands-on activity and as a presentation of original devices from the scientific instrument collection. Hands-on activities were designed to help solve several practical problems presented to the students. They built a type of Volta pile and tried to verify its operation; they repeated Oersted's experiment with a current-carrying wire in order to deflect a magnetic needle in a particular way; and they studied optical telegraphy and built a simple model of a Morse telegraph. Having been presented with the original scientific instruments, students were able to compare their own material manipulations with them and understand them as witnesses of past developments in science, their application, and their sociocultural significance.

Additionally, there have been recent attempts to teach through the analysis of historical instruments. In a fairly simple manner, this can be done by examining devices in their showcase in a museum. There have also been attempts to teach material culture through the analysis and contextualization of historical artifacts that may even be (or at least have been) part of everyday life (Anderson et al. 2011; Cavicchi 2007, 2011).

46.5 Conclusion

The analysis of several historical-investigative approaches has shown that the ideas of science as both practice and culture are often considered in science education. Over the past three decades, research into history and philosophy of science has strongly emphasized the constitutive role of experiments, instruments, and material procedures in science and their close relationship to the development of theoretical ideas. During that time, experiments in science have not been restricted to a mere means of testing ideas or hypotheses. In the aftermath of the practical and material turn in HPS, metaphors like the "mangle of practice," as Andy Pickering (1995) puts it, guide our understanding of science as a complex interaction of theoretical, material, and human agencies. Such complex views on how science works hardly match any cookbook-style idea of a single scientific method.

Straightforward epistemologies do not match what recent research in HPS has discovered about the idiosyncratic roles of experiments, instruments, and material procedures in science; hence, a single "big story" about science as a linear inductive, deductive, or hypothetic-deductive endeavor can hardly be told anymore. In this respect, the idea of a case study or a narrative about a particular event, scientist, experiment, or any other occurrence in science might actually generalize ideas about science, rather than define what science is or should be.

Even though the educational benefits of practical work in science education have been stressed for a long time, the current status of experiments in science teaching, in general, as a means for enhancing students' understanding of NOS is still weak. On the other hand, "verification labs" have been widely refuted by historical-investigative approaches. Practical work, according to historical-investigative approaches, is not restricted to the manipulation of equipment and materials or to a mere inductive endeavor. Manipulations of materials and instruments are, instead, a means for the development of the scientific ideas and skills of students who reflect simultaneously on their own investigations and their multiple relations to historical contexts.

In the practical and material turn in HPS and science studies, scholars focused more on detailed accounts of processes and practices in science. Laboratory diaries, notebooks, materials, and instruments, alongside the more traditional sources of letters and publications of scientists, become regarded as a rich resource for detailed accounts on how science works. This development is mirrored by recent attempts to make use of such resources for educational purposes. Through the analysis of laboratory notebooks and practical work with replicas of historical instruments, scientific investigations transform into a detailed process.

Alongside the practical and material turn in HPS, case studies about how science works gained increasingly more attention in science education. The Harvard case studies (Conant 1957) often have been quoted on the subject. Recently, case studies have had a stronger focus on learning about NOS in an explicit reflective manner. They offer several opportunities for students to develop their own investigations in close relation to the history of science (e.g., Allchin 2012; Clough 2011; Höttecke et al. 2012). Other approaches, like "critical exploration," (Cavicchi 2006, 2007) emphasize the role of reflected investigations of phenomena or technical devices, framed by historical contexts.

Regarding the use of instruments in science education for investigating material, as well as historical entities, a wide array of options have been offered, beginning with the use of authentic materials and instruments up to the use of modern ones. Each option has its specific advantages and suffers from particular problems. While the use of modern materials and instruments is hardly useful for reenacting and exploring the material culture of science, the use of replicas or even original instruments from the past suffer from a lack of availability or even usability for several teaching purposes. Hence, the relevance of each approach depends highly on where learning will take place (e.g., formal learning at school or informal learning in a science museum) and which teaching objectives will be targeted (e.g., NOS, conceptual knowledge, process skills).

In science museums, historical-investigative approaches appear to be quite innovative. Since the traditional goal of science museums was usually to balance the objective of protecting a heritage with that of enabling science learning, new ways for exploring the past with hands-on activities have been established which encompass both objectives. Here, approaches have been developed which allow visitors' hands-on activities, together with a careful display, or even use, of instruments of the past.

Whether or to what degree historical-investigative approaches will be disseminated and implemented widely is a matter of future research, as are the concomitant limiting factors or problems of such implementation. Scholars (Barab and Luehmann 2003; Höttecke and Silva 2011) have pointed out that teachers are the gatekeepers for any curricular innovation. Whether a wide and successful implementation will ever happen depends, at least in school science teaching, not only on the future design of curricular and standard documents but also on whether historical-investigative approaches actually will meet the needs and desires of science teachers. Therefore, materials for teaching and learning should be designed in a way that allows for a flexible and open use (Valk and Jong 2009).

Some of the above-discussed approaches explicitly refer to inquiry-based learning (Allchin 2012; Höttecke et al. 2012). From research regarding teachers' perspectives on inquiry-based learning, we already know that their general beliefs about successful science learning are linked to their beliefs about laboratory work and inquiry (Wallace and Kang 2004). Open-ended activities, which comprise discussions about scientific controversies or uncertain scientific evidence, will possibly alienate science teachers (Newman et al. 2004). Teachers often make detailed plans for instructional units which result in inflexibility in their reactions to students' ideas and products (Schwartz and Crawford 2004). This makes it a challenge to present science as inquiry or an open-ended activity (Roehrig and Luft 2004). The science teachers' expectation of having ready-made answers and safe content-knowledge (Höttecke and Silva 2011) may disincline them to accept historical-investigative approaches in science teaching. Science teachers need to know how to deal with new, emerging perspectives in the context of NOS. They should be able to organize open-ended investigations and moderate student-centered discussions. In general, they have to develop specific professional repertoires for teaching NOS successfully within any of the historical-investigative frameworks. Whether or not they succeed will depend on their readiness and willingness to leave established trails of teaching science behind and on their future professional development for teaching HPS in science education. The design of teaching materials following any of the historical-investigative approaches has to consider these conditions when planning for and establishing their successful implementation.

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Chapter 47
Science Teaching with Historically Based Stories: Theoretical and Practical Perspectives

Stephen Klassen and Cathrine Froese Klassen

47.1 Introduction

In recent decades, a trend has evolved in educational literature that emphasizes the potential of narratives, especially the story, to improve teaching and learning.[1] These studies approach the subject from both a methodological and theoretical perspective. Their authors purport that science stories illustrating the related abstract concepts engage and motivate the learner emotionally and intellectually. Further to that, this chapter examines the nature and structure of the science story and its capacity to provoke certain kinds of student responses that promote the learning of science. Historically based stories, in particular, promote the desired student interest and motivation by presenting humanistic episodes that explicitly include scientific content.[2]

The reasons for incorporating stories in teaching are summarized by Noddings and Witherall, who assert that

> we learn from stories. More important, we come to understand—ourselves, others, and even the subjects we teach and learn. Stories engage us. … Stories can help us to understand by making the abstract concrete and accessible. What is only dimly perceived at the level of principle may become vivid and powerful in the concrete. Further, stories motivate us. Even that which we understand at the abstract level may not move us to action, whereas a story often does. (Noddings and Witherell 1991, pp. 279–280)

Well-constructed and effective stories stimulate students' imagination and, thereby, produce affective engagement during learning episodes. The motivating effect and the vivid and powerful perceptions of stories take place largely at the

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[1] For example, see Egan (1986, 1989b), Kenealy (1989), Klassen (2009a), Kubli (1999), Metz et al. (2007), Solomon (2002), and Stinner (1992).

[2] See Hadzigeorgiou et al. (2012), Klassen (2009a), Kubli (2006), and Solomon (2002).

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emotional level, which is an insight in education that has only recently been explored. Yet, it has, likely, always been apparent to good teachers that stories make learning experiences memorable. The story approach originated within a general educational perspective and has, subsequently, been adapted for use in science education.

This chapter is about stories in science teaching and learning that are, at least initially, in written form and may be communicated to students in that form or narrated by a teacher or student. As readers will appreciate, the task of writing an effective story is a highly technical and challenging creative undertaking which is not the forte of every science teacher or educator. Before such writing can be carried out, the ambiguities that exist in the use of the terms "narrative" and "story" as applied in the science education context must be examined and removed. The terms "story" and "narrative" in this context are used in the literary sense and not in the broad, generic, and undefined sense that prevails in common usage.

There is significant evidence supporting the effectiveness of science stories to improve learning, and appropriate methods exist for integrating them with instruction systematically. The model of the story as the reenactment of a type of learning process and the role of the story in generating a romantic understanding of science are two pedagogical bases supporting the story approach. While stories serve, among other functions, to improve student motivation, the elaboration of theories and research on student engagement, motivation, or interest are beyond the scope of this chapter. The story form that is elaborated contains science concepts and, at the same time, emphasizes the humanistic dimension of science—an indispensible element of such stories and a critical feature of the only two empirical studies undertaken in this area to date. The humanistic aspect requires the incorporation of the historical accomplishments of notable scientists, necessitating the use of history of science to form the basis of the science stories. Stories need to be reasonably faithful to nature of science criteria, which is a reason for using history-of-science cases as the background for stories.

This chapter deals with stories that are historically based, as opposed to strictly fictional stories, in accordance with most of the literature in the field. The discovery of a good historically based story is like the discovery of a hidden treasure. Perhaps, the fascination for students arises from the romance of far-removed events with participants who had the same kinds of hopes, dreams, and struggles as we, and yet, in a very different environment. Good teachers often employ such stories in their teaching. They have found, like Swiss science educator Fritz Kubli, that "bare bones do not make an appetizing meal" for students (Kubli 2005, p. 520). Historically based stories (sometimes called "cases") are a valuable, some would say essential, part of providing a rich and diversely connected context for student learning.

Early theoretical work on stories has, to a large extent, centered on explaining why stories are expected to make learning experiences memorable. Some studies have focused on the idea that stories stimulate an emotional response in the listener or reader (Egan 1986, 1989a, b; Miall and Kuiken 1994). Others have argued that the story is a device that imposes coherence on a set of events (Kenealy 1989), which makes it a suitable vehicle for the integration of history of science in science instruction. The inclusion of historically based stories in science teaching has been advocated and attempted by a growing number of science educators.[3] Recently, a theoretical foundation for the use of narratives in the science classroom has been developed.[4] Yet, the observation of Bruner, in (1986), that "in contrast to our vast knowledge of how science and logical reasoning proceeds, we know precious little in any formal sense about how to make good stories" (p. 14) still rings disturbingly true today. This work is, in some sense, a response to the 25-year-old lament of Bruner.

47.2 An Overview of the Literature

A review of the scholarly literature on the theoretical basis, desirability, and use of stories (and narratives in general) in science classrooms over the past 15 years reveals that surprisingly little work has been done in this area (see Table 47.1). The list includes all relevant, peer-reviewed papers published in scholarly journals that deal with what are purported to be science stories, as opposed to other narrative forms. Not included in the list is the paper by Tao (2003), who used comic strips based on various historical "stories."

Bruner's early observation concerning how little was known about creating good stories was followed with his recommendation a decade later that we "convert our efforts at scientific understanding into the form of narratives" (1996, p. 125). In the literary field, "making good stories" is a matter of course, but this is not so in science education. The literature search yielded only 18 scholarly papers—which we categorized as advocacy, theoretical, descriptive, exemplar, or empirical—that have been published since Bruner's 1996 recommendation. Table 47.1 reveals that the literature on the use of stories in science teaching has been sparse up until 2005. Thereafter, the publication rate has increased, although not to a dramatic extent. Much of the literature is theoretical in nature, attempting to establish the features of stories that will likely contribute to their effectiveness in teaching science content and the nature of science. It describes instances in which stories and narratives have been used in classrooms but without a rigorous analysis of their success. In some cases, the literature is more explicit in describing the use of stories and includes the actual story used in the classroom, serving as an exemplar of the approach. The study of Negrete and Lartigue (2010) presents data of students' performance after listening to what the researchers call "stories" in comparison to factual summaries of the science content. The data, however, serve only to establish a rating scheme for the effectiveness of stories, the "stories" themselves being excerpts of much longer popular science writings that were not written to portray science in the sense being discussed here.

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[3] For example, see Kenealy (1989), Klassen (2009a), Kubli (1999), Martin and Brouwer (1991), Stinner (1992), and Wandersee (1990).

[4] For example, see Avraamidou and Osborne (2009), Klassen (2010), Kubli (2001), Metz et al. (2007), and Norris et al. (2005).

Table 47.1 A listing and summary of scholarly publications on the use of stories in science teaching

Author(s)	Year	Type	Summary
Hadzigeorgiou, Klassen, and Froese Klassen	2012	Empirical	Presents the romantic understanding framework for science stories and a quasi-experimental study demonstrating significant advantages for student learning about ac electricity through the story of Nikola Tesla
Clough	2011	Descriptive	Describes the process of developing 30 historical short stories
Klassen	2011	Exemplar, descriptive	Presents the design of a historical story surrounding the photoelectric effect and describes its use in the classroom
Klassen	2010	Theoretical	Presents a theoretical description of the linkage of the science story to a type of conceptual change
Kokkotas, Rizaki, and Malamitsa	2010	Descriptive	Presents the theoretical basis and describes the classroom implementation of a historical story on electromagnetism that yielded positive results described through examples of student journal entries
Negrete and Lartigue	2010	Theoretical, descriptive	Presents an evaluation scheme for using science stories with a brief description of a classroom study using stories
Avraamidou and Osborne	2009	Theoretical	Presents a case for the use of narrative in science education as a way of making science meaningful, relevant, and accessible to the public
Klassen	2009a	Theoretical, exemplar, empirical	Develops a basis for writing historical science stories along with an example, its use in a classroom, and the results in terms of student-generated questions
Isabelle	2007	Descriptive, exemplar, advocacy	Describes a classroom study teaching through a story and recommends the strategy to teachers, although not discussing demonstrated benefits of the case at hand
Klassen	2007	Exemplar, descriptive	Describes the design and classroom use of a historical story surrounding the first Atlantic cable
Metz et al.	2007	Theoretical	Presents a basis for constructing and using stories in science teaching
Hadzigeorgiou	2006	Descriptive, exemplar	Discusses the potential of stories in teaching and learning physics and presents a historical planning framework for teaching current electricity
Kubli	2006	Theoretical	Presents a basis for effective use of storytelling in the science classroom
Norris et al.	2005	Theoretical	Presents a discussion of the problems and potential of using science stories with explanatory content and the theoretical basis of such stories
Solomon	2002	Theoretical, advocacy	Illustrates types of science stories that might be used and their purposes
Kubli	2001	Theoretical	Presents a theoretical basis which science teachers can employ to become better storytellers
Milne	1998	Theoretical	Discusses the assumptions behind certain perspectives contained in stories and the desirability of these perspectives
Knox and Croft	1997	Descriptive	Describes the use of story in a meteorology classroom with positive responses from students but did not demonstrate learning benefits

All of the literature listed in Table 47.1 utilizes or advocates historically based stories, with the exception of Avraamidou and Osborne (2009), who advocate for stories that are exclusively fictional. All of the exemplars or empirical studies are historically based.

While some of the papers overlap between or among the designated categories, as outlined in Table 47.1, overall, ten of the papers are theoretical, eight descriptive (with or without exemplars), and only two empirical. Five papers include exemplars. With the exception of Hadzigeorgiou, Klassen, and Kubli, researchers have not pursued their initial study with further research in the area. The table reflects the movement towards empirical approaches, which is vital in the development of this research area. The two empirical studies are summarized in greater detail below.

47.2.1 Empirical Studies Utilizing Stories in Science Teaching

The 2009 study of Klassen (2009a) presents a literary framework for the construction of stories that is based on Norris and coauthors (2005) and Kubli (2001). A story about Louis Slotin and the beginnings of the science of radiation protection is presented as an exemplar, and a classroom study utilizing the story as a door opener for an experimental investigation is described. Student responses to the story were gathered in the form of student-generated questions at the end of the story. Klassen sees a major purpose for using door-opening science stories as raising questions in students' minds. Not only is the raising of good questions important from a constructivist, pedagogical point of view, but also there is reason to believe that questions are implicitly involved in theory formation. Therefore, evidence for the generation of good questions as a result of listening to the story would serve as a major indicator that stories tend to enhance learning. The data presented in the study support the conclusion that good questions were, indeed, generated as a response to the story. The largest number of questions were of a type that suggested higher-level thinking, rather than simple, factual ones typically introduced by the interrogatives "when," "where," and "who." There was, however, evidence that the students were inexperienced with generating well-framed questions, as indicated by a number of questions which appeared, on the surface, to be polar questions (requiring "yes" or "no" responses).

Hadzigeorgiou, Klassen, and Froese Klassen (2012) provide details of an empirical study utilizing a story, based on Nikola Tesla's life and work, that was written to embody the elements of romantic understanding (see Sect. 47.5.2 for elaboration of romantic understanding) in order to teach the concepts of alternating current electricity. The study design was quasi-experimental, with the experimental group of students ($n=95$) only listening to the Tesla story and the control group ($n=102$) receiving conventional instruction with the mastery-teaching technique. Both groups were given the same open-ended, paper-and-pencil concept test on alternating current electricity. All students were encouraged to make journal entries.

The authors determined that the students who were encouraged to understand the concept of alternating current romantically—that is, through the story—became more engaged with the science content compared to students who were taught explicitly by conventional instruction. A quantitative analysis of students' journal entries revealed that of the students in the experimental group, 96 % made relevant journal entries, whereas only 55 % in the control group did so. Some of these students also demonstrated imagination and curiosity in their journal entries, which was not observed in the control group. Additionally, they undertook relevant independent research on their own initiative, which was indicative of the transformative effect of the storytelling instruction. This was a notable difference from the students in the control group who did not undertake any related reading outside of class, according to the analyses of the teachers' observations. The results also affirmed the effectiveness of teaching alternating current electricity through the Tesla story in the statistically superior concept-test results of the experimental group over the control group. Data on the question requiring an explanation of the concept of alternating current, for example, showed that 72 % of the experimental group versus 41 % in the control group gave an acceptable response. When the test was repeated 8 weeks later, 67 % of the experimental group versus 31 % in the control group gave an acceptable response, suggesting not only superior understanding but also greater long-term retention. A content analysis of the student journals of the experimental group revealed that at least two characteristics of romantic understanding were identified in all journals and that two thirds of the students in the experimental group made associations with the science content in their demonstration of the characteristics of romantic understanding.

The authors conclude that

> [t]he implication of this study for science education is that a particular type of a science story, that is, a romantic story, has significant potential for improving learning in the discipline. Such a story should be based upon human qualities, heroic or otherwise, that evoke wonder and give students the opportunity, through the plot, to associate science content with such qualities and simultaneously experience a sense of wonder. (Hadzigeorgiou et al. 2012, p. 1134)

47.3 Explication of Key Concepts: Narrative, Story, and Science Story

Narrative is a humanistic mode of expression that has as its core purpose the recounting of related events involving characters. In the most elementary sense, a narrative tells of someone having done something. Traditionally, narrative has been distinguished from exposition, description, and persuasion, which are other modes of communication (Connors 1981). Various scholars have used the terms "narrative" (Kubli 1998; Martin and Brouwer 1991), "story" (Egan 1989b; Kenealy 1989; Kubli 1999; Stinner 1995), "thematic" (Holbrow et al. 1995), or "storyline" (Arons 1988; Coleman and Griffith 1997; Stinner 1995) to describe their approach in using this mode in science teaching. The narrative approach has a spectrum of possible adaptations, ranging from the smallest stand-alone story element, such as the vignette

(Wandersee 1992) or anecdote (Shrigley and Koballa 1989), to the largest story-like structure, such as a curriculum unit unified by a theme (Gorman and Robinson 1998; Holbrow et al. 1995) or storyline (Coleman and Griffiths 1997; Stinner and Williams 1998). These various proposed approaches, other than the story itself, have not been put to the test in formal research studies and will not be elaborated in this chapter. There is no recent science education literature describing the use of other forms of narrative. Some time ago, Shrigley and Koballa (1989) described the anecdote and Wandersee (1990) described the vignette and its use in science teaching. Neither of these two forms was developed any further in the literature nor studied through research.

The notion of narrative is broad, and the term does not have a categorical definition in the literature, in contrast to the literary notion of story. Moreover, in the narratological literature, it is not distinguished clearly from the act of storytelling, which is intricately connected to voice, narrator, and other oratorical devices. For reasons such as these, the discussion in this chapter, of necessity, has certain delimitations. The first of these is the definition of "narrative" itself. The literature on narratives is complicated by theorists using varying terminology for similar concepts, making the task of definition challenging. Specifically, the terms "narrative" and "story" are frequently used interchangeably and then either not defined or defined in a way that is not adequate for application in a particular context. To aid in the sorting out of related and, possibly, conflated terminology, the core constituents of narrative, namely, its "raw material," will be distinguished from the delivery of narrative material, the reception and personal reconstruction of narratives, and the specific ways and contexts of using narrative material. Defining narrative in terms of core constituents has the added benefit of providing a "litmus test" for educational material that claims to be "narrative." The definition of narrative constructed here incorporates the insights of Altman (2008), who presents a particularly succinct history of narrative definitions and divides the definition of "narrative material" (p. 10) into categories.

Whereas the concept of "narrative" is broad and generic, the concept of "story" has specifically defined attributes. In concurrence with Altman (2008), this chapter makes a distinction between "some" narrative and "a" narrative (p. 17), in that "some" narrative is a narrative excerpt and "a" narrative is a complete narrative episode with a beginning, middle, and ending—one of the special requirements of a story. In this chapter, the term "story" is not used in the generic and loose sense, as in popular and even in some scholarly literature, but in its defined sense that is identified with a specific literary form. Such a story also requires a central role for the main character, who is involved in some type of conflict that compels him or her to make a critical decision, which, ultimately, determines the outcome of the story.

The definitions of narrative and story presented below additionally make use of the insights of Klassen (2009a, 2010), Kubli (2001), and Norris and coauthors (2005) but utilize only elements and characteristics that are essential for the construction of narrative on the part of the teller or writer, as opposed to its reception or its expression in particular settings or for particular purposes. In this respect, the definitions are, of necessity, based on structuralist approaches to narrative—an insight which is crucial for the operationalization of narrative theory in the science education context and which has heretofore not been recognized by researchers attempting to formulate a definition of narrative or story.

47.3.1 The Concept of Narrative

In view of the considerations presented above, narratives have five fundamental elements, as outlined below, in some instances with illustrations. Since stories constitute a class within the narrative genre, the aspects of narratives apply equally well to stories. The purpose of presenting a definition of narrative is not only for clarification but for subjecting writing that purports to be narrative, or even story, to a criterion-based test that can ascertain whether it can, justifiably, be characterized as a narrative. For writing that consists, for example, of a mixture of narrative and exposition, it would be relatively easy and uncontroversial to analyze the text sentence by sentence for its degree of narrativity. While a narrative does not necessarily contain all of the elements of a specific class of narratives, such as the story, it must, by definition, include the features of characters, actions, situations, consequential coherence, and past time.

47.3.1.1 Characters

The most basic element of any narrative is that it involves at least one character who is the representation of a person or persons. In historically based science stories, the characters are real people (usually scientists), and their story is a form of historical interpretation. Altman (2008) points out that while some definitions of narrative have omitted the role of characters and concentrate, instead, on the events which give rise to plot, characters are essential and central since they are the agents that produce the action.

47.3.1.2 Actions

The actions of the characters, sometimes called “events,” are the “raw material” of the story, but, by themselves, they produce only chronologies that lack interest; they are not narratives. In historically based narratives, the actions of the characters are obtained from the historical records. Agency, of necessity, creates a personal dimension; therefore, it becomes necessary to attribute thoughts or spoken words to the protagonist, especially. The preferable method of obtaining such expressions is to adapt them from writings of that person or other relevant historical records. If thoughts or spoken words not obtained from the historical record are added for effect, these must not contradict the history.

> *Example:* Eighteen-year-old Alessandro Volta was passionate about electricity, indeed so passionate that he announced to his somewhat startled family, "I'm not going to university! I would rather spend my time on investigating electrical phenomena."[5] Alessandro's family was used to his surprising turns.[6] As a child, Alessandro had not learned to speak until he was age four, which had led his alarmed parents to think that he might be slow-witted, but then little Alessandro suddenly began to develop at a furious pace, out-performing all his school mates.[7] In his father's words, "We had a jewel in the house and did not know it!" And so, at age eighteen, the gifted young Volta launched into a scientific career by beginning to write to the leading scientists of the day about his ideas, and, surprisingly, they replied. (Klassen 2009b)

In the above example, all of the details are historically accurate or plausible. The words attributed to Volta are plausible based on the record. The words attributed to Volta's father are a part of the historical record explicitly.

47.3.1.3 Situations

Narrative has situations or states insofar as the character responds to them or helps to create them. The situational aspects of narratives that represent a state of affairs or a state of being are often not separable from the actions from which they result. An example extracted from the story "The Soul of Solar Energy: Augustin Mouchot," written by the authors, is given here. The first segment ends with a state of being, followed by an action, followed by a changed state of affairs in the last segment. The situational sentences are italicized.

> As Augustin arose in the chill of the dawn, his thoughts drifted to what he had just been reading about the energy of the sun. Physicist Claude Pouillet had written that every square meter of the Earth's surface receives about 10 Calories of energy every minute. Augustin chuckled, "Not a very useful fact on a cloudy day like today!" Then, a flash of inspiration crossed his mind: "It's not cloudy every day. Wouldn't it be possible to heat enough water with the sun's light and spare the fire that is only meant to heat the house?" *While he made the last preparations to teach his geometry class, he could not get his mind off the energy issue.*
>
> …
>
> Over the next few months, Augustin immersed himself in his new project of building a solar energy collector despite having to teach his regular classes.
>
> …
>
> *Soon, Augustin had completed the construction of his first solar water heater, which was capable of holding three litres of water.* Lucky for him, it happened to be a cloudless day! Excitedly, he placed the boiler and mirror in the direct sunlight. To his amazement, the water, which he had initially measured to be 15 degrees, boiled in just an hour and a half. From then on—on sunny days—Augustin saved himself the bother and the expense of coal-heated water when he bathed. (Klassen and Froese Klassen 2012, italics not in original)

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[5] The discourse is imaginary but plausible.

[6] A reasonable assumption, based on the historical record.

[7] Part of the historical record (from here to the end of the segment).

Fig. 47.1 The causal structure of a story (From Klassen 2010)

47.3.1.4 Consequential Coherence

As mentioned above, by themselves, the actions of the characters produce only chronologies, which lack interest. They are neither stories nor narratives. Narratives and stories require that the events be causally linked (see Fig. 47.1 for a representation of the causal structure of a story). The story is written in such a way that it is clear that the actions of the characters produce the changes in the state of affairs. Besides the fact that the events of the story follow one another in time, it is especially the causative linkage of events that produces the perception of the flow of time. Of course, the entire story need not be structured in a strict chronological sequence, as the story might contain flashbacks and flash-forwards; however, it must have a consequential sequence.

> *Example of a chronology without consequential coherence:*
> Ohm took up a teaching position in Cologne;
> he performed an experiment to determine resistance;
> and he published his experiment.
>
> *Example of a passage with consequential coherence:*
> Ohm understood the mathematical theory of heat;
> he applied the theory to electricity by analogy;
> and as a result, Ohm understood the mathematical theory of electrical resistance.

47.3.1.5 Past Time

The events of a story take place in the past and are recounted. The science-based story is historical, and it would be a contradiction in terms to write it in the present tense. Use of the present tense is reserved for other modes of communication, for example, exposition.

47.3.2 Science as Historical Narrative

The scientific work done and the results achieved by investigating scientists have to be communicated to other scientists. Their results cannot readily be separated from the experiments that were undertaken. The carrying out of experiments is a human endeavor, replete with false starts, errors, and frustrations. This phenomenon significantly increases the potential for historical narratives to supplement the published results in the scientific literature. R. G. Collingwood (1945) has carried this line of reasoning further by claiming that history is, in fact, a more fundamental form of thought than the science about which it reports. He writes that

> the scientist who wishes to know that … an event has taken place in the world of nature can know this only by consulting the record left by the observer and interpreting it, subject to certain rules, in such a way as to satisfy himself that the man whose work it records really did observe what he professes to have observed. This consultation and interpretation of records is the characteristic feature of historical work. … I conclude that natural science as a form of thought exists and always has existed in a context of history, and depends on historical thought for its existence. (Collingwood 1945, pp. 176–177)

What Collingwood describes about scientific work appears very much like the process of historiography. Yet, current-day scientific publications usually exclude the human dimension of the work that brought about certain scientific conclusions or theories in science. In that sense, scientific publications are a specialized, rational reconstruction of history. Perhaps, it would not be an exaggeration to say that science has become a form of dehumanized and decontextualized history. An attractive method of interesting the disinterested young student in science is to portray it differently—more realistically, from the human and contextual perspective as a specialized narrative or story.

It is important to emphasize that historical chronologies, by themselves, are not narratives, as they have no causal structure. In the absence of clearly defined criteria, such as causality, many of the terms in the scholarly literature, such as thematic approach, storyline, vignette, anecdote, or story-like structure, must be subjected to closer scrutiny. The existence of this definitional vagueness emphasizes the importance of establishing a “litmus test” for both narrative and story, in order to produce a standardized vehicle for the delivery of narratives and stories and for the purposes of research. The definitions that have been given above may be taken as such a litmus test.

47.3.3 The Concept of the Science Story

The essential elements of a story include those of narratives that have been described. Two further components are necessary to create the classification of story within the broader narrative form, namely, a defined plot structure and agency—the critical choice made by the protagonist. The science story, a classification within the class of story, includes an additional element, namely, science and NOS content. Aspects of narratives or stories that are specific to their method of delivery or to their reception by the listener or reader, while potentially important for the effectiveness of the story, are not considered as core constituents in its written form.

47.3.3.1 Plot Structure

The plot structure of a story consists of a beginning-middle-end structure that frames the story and creates a stand-alone unit. In general, the story structure typically includes an introduction, rising action that includes some sort of conflict, a climax, and a resolution or conclusion. In the conceptualization and construction of the story, planning the plot is crucial and involves a creative interpretation of the history that identifies fascinating elements in the record and combines them with the relevant science. Planning a plot requires selecting historical details to form a coherent story. Specifically, a typical plot (a) begins by "setting the scene" in some manner, (b) followed by the presentation of a problematic situation (c) which reaches a crisis, (d) necessitating a critical decision made by the main character (e) that results in a climactic moment, and (f) concludes in a resolution of the situation, which can be either positive or negative.

47.3.3.2 Agency: Critical Choice Made by the Main Character

In a story, the role of the main character is crucial and will affect the outcome of the story through a consequential, critical choice that he or she has made. Crucial choices are integral to the typical plot structure as outlined above.

> *Example:* Grabbing the hemispherical beryllium shell by the thumb-hole on the top, Lou carefully lowered the top half onto the bottom half covering a hemispherical plutonium shell, which, in turn, covered the polonium initiator, holding them apart with a screwdriver. As he rotated the screwdriver slightly this way and that, the shell moved up and down. From across the room the familiar crunching sound of the Geiger counters swelled and ebbed. Then it happened. No one knows what broke Lou's concentration, but something did. The screwdriver slipped and clattered to the floor and a blue flash filled the room as the top shell touched the bottom, releasing a torrent of neutrons and gamma–rays. Time seemed to come to a screeching halt. Almost instinctively, Lou, using both hands, grabbed the lethal assembly and flipped the bomb-shell off the table and onto the floor with what seemed a deafening crash. "Well, that does it—I'm dead!" Lou heard himself say. "Tell me this is a nightmare," he thought. *But it wasn't.* (Klassen 2009a, p. 421)

47.3.3.3 Science and NOS Content

The scientific aspects of the historical episode that are contained in the story should be embedded at the appropriate points in the story in such a way that they flow naturally with the story. In some cases, it will be possible to include the scientific concepts developed sufficiently to allow students to comprehend them fully. In other cases, the scientific questions and issues will be included as questions, issues, and problems which need to be developed more fully in activities that follow the story. Such content should be included from the perspective of the characters of the story and be interwoven in a narrative manner as much as possible.

Similar considerations reflect the NOS issues that are contained in the story. Sometimes these issues may be stated explicitly in the flow of the story, and at other times, these will be raised more indirectly and will need to be followed with a student activity that will focus on the issue and clarify it. The following example is taken from the story used for the experimental intervention in Hadzigeorgiou and colleagues (2012) (the reader is referred back to Sect. 47.2.1 for a description of the study):

> *Example of embedding science content:* In an attempt to demonstrate the dangers of AC power, Edison sponsored an electrical engineer to travel the country electrocuting animals with both DC and AC. Because the frequency of AC confuses the heart, animals that are electrocuted by AC die, whereas animals that are electrocuted by DC are stunned but survive. Edison used these so-called "experiments" to contrast the danger of AC with the relative safety of DC. We know that the effect of any type of electric current on a human being is very difficult to predict, as it depends on a number of factors (for example, the condition of the skin, amount of fluid in the body, and the point of contact). Tesla, however, had been experimenting with very high frequency currents, which, as he, showed, did no harm. With his theatrical flair, Tesla could draw sparks to his own fingers and even walk through sparks without being hurt. He had realized that the high frequency of the current kept it on his skin. It was this strange effect, known as the skin effect, which made Tesla famous. He even sent sparks to the audience, making people realize that AC current, at least as used by him, was safe. (Hadzigeorgiou, Froese Klassen, and Klassen 2011)

47.4 The Non-scripted and Scripted Approaches to Using Stories

The story approach in teaching science, as described in this chapter, is based on the use of science stories that are constructed according to the concept outlined above. What is not included in this approach is that of the non-scripted story, told spontaneously, randomly, and, perhaps, frequently. In the story-permeated approach—the spontaneous injection of non-scripted narratives—the narratives may range from a recounting of the teacher's experiences to anecdotes that may or may not pertain to curricular content or concepts. Teachers who use stories in this fashion must have expertise not only in the telling of stories, but they must have a wide repertoire of good story material at their disposal. Such an approach is largely informal and more difficult to fit into a definitive framework than the scripted-story approach. Because of the number of uncontrolled variables, this approach is virtually beyond the scope of research studies.

The scripted-story approach—the formal, planned integration of scripted stories—pertains specifically to the curricular concepts taught. Particularly teachers inexperienced in storytelling and lacking a repertoire of science-story material can enhance their instruction with the scripted-story approach. Scripts allow for a measure of structure, which is not necessarily the case for spontaneously injected narratives. The distinction between the two vehicles is fundamental to each approach for integrating narratives and stories in science instruction. A "narrative," as already defined, consists of the recounting of actions produced by characters, while a story is more rigidly defined by its structure—that the events that happen, revolving around the protagonist, must be interrelated and consequential (i.e., have a consequence for the protagonist and, possibly, others).

Both of these approaches also concern the act of storytelling itself. This chapter deals primarily with story *crafting*, as opposed to story *telling*. The latter consists of the performance aspect of storytelling where the narrator becomes the performer and requires proficiency in the relevant performance art. While it is indisputable that the manner in which the story is told plays a vital role and is certain to influence the students' level of enthusiasm and possible engagement with the story, it is not within the scope of this discussion to deal with the oral presentation of stories as it is presented in the literary or theatrical tradition (learning how to become an effective storyteller, both in terms of retelling existing stories and spontaneously creating new stories). For the storyteller of the spontaneously injected narrative, the challenge of telling the story from a first-person participant perspective is enormous, especially when coupled with the fact that this method, when dealing with historical information, already presupposes expert knowledge of the history of science on the teacher's part. Conversely, the planned injection of scripted stories demands that the teacher must become aware of the existence of available science stories that pertain to particular science concepts and be able to integrate them meaningfully and strategically. This can be performed by a novice teacher.

Both the story-permeated and scripted-story approaches share a facet of the narrative act that is largely beyond the control of the teacher, other than that he or she may provide the stimuli for it, and that element is the inner narrative taking place in the student's mind in response to any new learning from the narrative itself or the embedded concepts. This inner dialogue is affected by the manner in which the story is told or read and may influence the level of student engagement and learning. The inner dialogue, which may focus on the storytelling act alongside the story, is complex, spontaneous, and beyond the storyteller's control.

47.5 Theoretical and Pedagogical Reasons for Using Stories

There is good evidence that in order to engender meaningful learning, it is essential that teaching and learning methods be imbedded in appropriate contexts (Kenealy 1989; Martin and Brouwer 1991; Roth and Roychoudhury 1993). Historical contexts address the "why" and "how" aspects of the development of science in a way that includes the scientists as living persons who are concerned with personal, ethical, sociological, and political issues. It is generally accepted that this form of presentation is likely to engender increased motivation in students. Such historical materials must not consist of mere chronologies but rather expose the settings in which discoveries were made in the form of stories (Stinner et al. 2003; Metz et al. 2007). The use of stories to teach science has both theoretical and evidential support apart from the contextual argument.[8] It is the literary story form, in particular,

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[8] See Egan (1986, 1989a), Hellstrand and Ott (1995), Kubli (2005), Miall and Kuiken (1994), and Norris et al. (2005).

that is known to produce consistent affective engagement (Miall and Kuiken 1994). This engagement also has a physiological basis. According to Miall and Kuiken, narrative techniques in the literary story "accentuate… activity in cortical areas specialized for affect" (1994, p. 392). The literary story adheres to the normal considerations in literature while making use of scientific and historical materials for its construction. Teachers who use such stories hope to capitalize on affective arousal in the form of increased student motivation.

The important role of the emotions in learning has been recognized only recently. Relevant, in this regard, is the research of neurobiologist Antonio Damasio on emotion and rationality. Damasio studied human subjects who had lost the ability to communicate information about emotions from one part of the brain to the other. He was able to support his hypothesis concerning the relationship between emotion and reason, which states that the emotions act as an arbitrator in rational decision-making and that without access to one's emotions, it is impossible to plan and make rational decisions (Damasio 1994). Educator Douglas Barnes demonstrates, in a research study of student group learning, that "unless pupils are willing to take the risk of some emotional commitment they are unlikely to learn" (1992, p. 87). Cognitive psychologist Pierce Howard, in a popular review of current neurobiological research, further explains the role of emotions in learning this way: "Experience arouses emotion, which fixes attention and leads to understanding and insight, which results in memory" (Howard 2000, p. 549).

At issue is the means by which emotion could be aroused in an appropriate manner in the teaching and learning situation. It is well established that stories have the ability to engage the emotions. Educator Kieran Egan (1989a, b) has long advocated the story form as the principle method of engaging students' emotions. Egan argues that the presentation of curriculum content through stories stimulates the imagination and evokes emotional response, thereby producing learning that more easily assimilates with long-term memory than learning produced by drilling and memorizing. The listener or reader engages with the story because she or he is encouraged to participate vicariously in the experiences of the protagonist. The kind of motivation produced by story is intrinsic, as opposed to the extrinsic motivation produced by a prescriptive teaching and learning episode (Mott et al. 1999). The story also provides an organizing structure for related knowledge and experiences (Mandler 1984).

47.5.1 Story as Reenactment of the Learning Process

It is noteworthy that the causal relationship of elements in a story (Fig. 47.1), which was described in Sect. 47.3.1.4, is structurally analogous to that of a type of conceptual change in the learning process (Fig. 47.2) (Klassen 2010). The schematic representation of conceptual change of Fig. 47.2 elaborates a temporal learning episode. The evolution of an event such as a scientific phenomenon (the learning episode) begins with the observation of the properties of the object (or entity) in question—the original state. The learner then observes a change in the state or properties of

Fig. 47.2 A temporal framework for conceptual change (From Klassen 2010)

the object. The enigma in the learning process is that the learner does not know ahead of time what the final state will be. There are unseen properties of the situation that resulted in or contributed to the change in state. Curiosity or the need to uncover and explain such hidden properties initiates the learning process. Provided that there is sufficient motivation, the learner will attempt to construct explanations for such unanswered questions, usually through a process of reenactment of the event on the basis of some explanatory mental model. The process can, for example, be applied to the experiment of Ohm and his subsequent attempt to explain it:

> The deflection of the magnetometer on Ohm's apparatus indicated a particular resistance to the flow of electricity;
>
> then a different length of wire was inserted into Ohm's apparatus;
>
> as a result, the deflection of the magnetometer on Ohm's apparatus indicated a different flow of electricity.

The process here consists of two experimental observations (states) with the experimenter's intervention between them. Experimental intervention often proceeds by an adjustment of one of the parameters. In order to construct a theoretical expression to explain his observations, Ohm wrote an equation that he already had good reason to believe explained the observations. Ohm replayed his series of experiments on paper by first assuming that the current flow through the wires was analogous to the flow of heat, which he understood. As the historical record shows in Ohm's own words (Magie 1965), Ohm was able to reproduce his experimental results by recalculating his model with the parameters set at suitable values, showing that his explanation was a good one. In this way, Ohm justified his theory. Ohm's method can be viewed as the process of reenactment of his theoretical expression using suitable parameters that resulted in a reproduction of the experimental observations. Clearly, the minimal story sequence of Fig. 47.1 is followed; however, the usual requirement that a story involve the state of a human agent is not met. What changes in the case at hand is an experimental observation. Of course, when the subject of explanation is an abstract concept, then the involvement of human agents occurs at a secondary level.

Klassen (2010) shows that just as the story form consists of a temporal sequence, some of the learning involves a similar temporal sequence. The story form will be most useful for learning if it becomes a part of the sensemaking process and contributes to the formation of long-term memory structures. In Ohlsson's model of sensemaking (1999), the learning process includes the reenactment of remembered events in light of new knowledge. The story form can similarly be viewed as a reenactment of the cognitive process that would normally be involved in order to learn the story content. The story consists of the recounting of a chronology of events that includes causative links between succeeding events. Remembering, retelling, hearing, or reading a story will then serve as a form of mental reenactment.

The structure of a story is just one part of the design of a good story. Other features of stories are, for example, the effect of the untold, suspense, irony, and lifelikeness, which might be designated as the story's literary qualities. These features tend to stimulate the emotions of the reader or listener. An artistically crafted story arouses emotions that, in turn, contribute to the integration of the story details with long-term memory (Klassen 2010). A well-crafted story should, therefore, contribute to better learning of a variety of content knowledge items. This is what anthropologists have maintained all along. In the distant past, stories were used as the most effective device for passing on the culture to succeeding generations (Levi-Strauss 1966). In the context of learning science, there is good reason to utilize the story as a productive application of this enduring method.

47.5.2 Story as a Stimulus for Romantic Understanding in Science

As established in Sect. 47.2, relatively little has been written or researched regarding the construction of stories in regard to their relationship to effective learning. A notable exception is the learning theory of Kieran Egan that advances the concept of romantic understanding. Romantic understanding, which by definition takes place in a humanistic context, may be defined as the ability to grasp the meaning of the features of subject matter in a manner that tends to be idealistic in expectation and glamorously imaginary, possibly even exotic and involving the potential for heroic achievement. During the period of their development when they exhibit romantic understanding (approximately between ages 8 and 15), children are attracted, for example, to literary characters who do heroic, but possible, things.

Egan identifies five vital means by which children at this stage make sense of the world and of experience and by which they mediate between the world and the mind. These means, which he calls "cognitive tools," become the specific characteristics of romantic understanding. They are (1) the humanization of meaning, arising from the realization of the humanistic dimension of all knowledge; (2) an association (even identification) with heroes and heroic qualities; (3) a focus on and confrontation of the extremes and limits of reality and experience; (4) a sense of wonder; and (5) the contesting of conventions and conventional ideas.

Hadzigeorgiou and colleagues (2012), in order to reflect these tools and the instructional strategy in the concept itself, conceive of romantic understanding as "the motivating insight that emerges through the combined engagement of the emotions and the intellect in response to a specialized text" (p. 1114). The instructional strategy of the story is the "specialized text," which specifically incorporates the various cognitive tools.

The humanization of meaning in the story is a natural outgrowth of the fact that it is human endeavor which generates scientific knowledge and that human emotions are an integral component of its creation. The human element in the science content is incorporated through the scientist's life and work. In Tesla's case, for instance, it was his personal ambitions, his humanitarian ideals, his uncommon ingenuity, and his frustration with the establishment that together contributed to his ultimate achievements (Hadzigeorgiou et al. 2012). The resulting captivation with Tesla is rooted in his admirable character traits and abilities. It is this aspect with which students identify and which inspires them to emulate notable scientists because they come to understand that they, too, can develop such qualities as they conceive of new human possibilities through the story.

Students are further attracted to the stories because they exemplify the extremes of physical reality, whether they manifest in nature, the lowest temperature or the smallest electric charge, or in the human experience, the fastest athlete or the longest flight. These extremes, along with the many fascinating and mysterious phenomena and astonishing ideas that abound in science, evoke a sense of wonder. Through this kind of experience, students become aware of their incomplete or mistaken knowledge, helping them see the science lesson in a new light and emotionally charge the new information to be learned. Another source of fascination with the story arises from the fact that many scientists had to struggle against firmly held beliefs and ideas that stood in direct opposition to their new-found knowledge. When learning about the obstacles that scientists, such as Galileo, Boyle, Volta, Tesla, Einstein, and Marconi, faced and that they stood firm in their convictions, students can realize the strength of human convictions which bring the human element into the science content.

47.6 Constructing and Utilizing Stories

47.6.1 *Utilizing History as the Raw Material for Science Stories*

The writing of a story that is meant to utilize history of science cannot proceed without considering what interpretation of history is to guide the selection and adaptation of historical materials. History of science is subject to a broad spectrum of possible interpretations. One end of the spectrum is what Herbert Butterfield (1931/1959) called the Whig approach to history in which history of science is viewed in light of current knowledge. Implicit in this approach is the assumption that current knowledge is superior to the knowledge of past scientists. Critics of the Whig approach object to applying current days' standards to history because historical figures operated in a different environment from that of today, with different assumptions and standards. There are also internal histories of science written primarily by scientists, some of whom participated in the events about which they wrote many years later. The purposes of such histories are to legitimize the science, to aid in the socialization of novices, and to provide exemplars that will be used as

Table 47.2 An evaluative list of features for the construction of a science story

Character(s) taken from history of science
Actions that are consistent with the historical record
Situations or states
Consequential coherence of the characters' actions
Past time
Plot structure with rising action and climax
Critical choice made by the main character
Appropriate science and NOS content

models for problem-solving (Kragh 1987). Internal history often provides an official version of the roots of the discipline that tends to romanticize the events and portray science as an inevitable consequence of the force of progress. Exposing students only to this version of history encourages a distorted view of the nature of science, not to mention of the history, itself. The other end of the spectrum of approaches is the localized view in which history is interpreted only in light of the knowledge and context of the time and place in question. This approach, referred to as horizontal history by Mayr and diachronical history by Kragh, has been criticized on the grounds that history cannot be interpreted when comparisons to the larger context cannot be made (Kragh 1987; Mayr 1990). Furthermore, it has been claimed that purely diachronical history, consisting of a chronology of events restricted to the local context (Kragh 1987; Mayr 1990), is uninteresting to the nonspecialist.

For the purposes of writing a story to serve as an introduction to, or framework for, the teaching of a topic in science, aspects of all of the historical interpretations mentioned may be present to a certain degree. Certainly, the overriding consideration will be to portray the history accurately by using the best original and secondary sources. Any account must also be sensitive to the practices, beliefs, and social mores of the time, albeit, taking into account the limited identification with these on the part of current-day students. Any story arising from the history must be sensitive to such possible areas of misunderstanding by students, all the while not implying current superiority. Of course, the history of an event in the discipline that has been written for students of the discipline cannot help but provide some degree of legitimization and socialization. The goal is to portray scientists as human beings, "warts and all" (Winchester 1989, p. v), in order to give students the opportunity to become affectively involved in the story of science. Usually, the listeners to such stories will have a substantial degree of empathy for the protagonists of the stories.

47.6.2 Guidelines for the Construction of a Story

Story construction is a creative process and should not be formulaic or constrained by a fixed format; however, it must contain essential elements that meet the criteria for a story. A framework for the writing of a science story as described in this chapter should be guided by its characteristic features. The elements that were elaborated in Sect. 47.3 comprise an evaluative list and are summarized in Table 47.2. These can be taken as guidelines against which to judge any science story.

47.6.3 A Framework for Incorporating Stories in Science Teaching

In the case of science teaching, the type of instruction being described here corresponds to *contextual science teaching* (Klassen 2006). The contextual method is described, in detail, elsewhere (Klassen 2006) and is called the story-driven contextual approach (SDCA). A brief overview of the method and its framework will be provided here. Klassen identifies five important contexts that are a part of effective science lessons. These are the (1) practical, (2) theoretical, (3) social, (4) historical, and (5) affective contexts. Each of these contexts should relate, in some way, to the scientific concept being taught and contribute to the overall meaningfulness of the learning episode and to the degree of engagement of the students.

47.6.3.1 The Practical Context

The practical context provides hands-on, laboratory-style investigative activities for the students. Ultimately, the practical context is meant to replace traditional "labs" in the "normal science" curriculum. Students who are potential scientists benefit from practicing as novice scientists, since they are only one step removed from being apprentices. Even students who have no intention of becoming scientists benefit from participating in an authentic activity that includes creativity and some intellectual challenge beyond guessing what the lab manual wants.

47.6.3.2 The Theoretical Context

Each lesson should, if possible, also contain a theoretical element. Research or paper-and-pencil type questions that can be formulated in a brainstorming session after the presentation of a science story tend to be meaningful and memorable for students. Here students are challenged to answer conceptual "why" and "how" questions about the issues raised by the story. In a typical class, students should perform both practical and theoretical investigations.

The manipulation of ideas in the theoretical context is meant to replace paradigm exemplars of the type that students learn in normal science education. Normal science education relies heavily on end-of-chapter questions to provide student learning experiences. These problems are usually contrived and remote from students' life experiences. In contrast, problems in the theoretical context emerge as a natural necessity in the course of investigations. Ideas or concepts take on meaning as they are naturally generated by the context. The theoretical context, however, is dependent on the practical context to provide a well-rounded learning opportunity. As in the practical context, students are cast into the role of being novice researchers.

47.6.3.3 The Social Context

The benefit of cooperation in assisting learning is a relatively uncontroversial fact, and the ability to work together productively in small groups is a skill recognized by science curriculum developers. The benefits are likely to accrue not only in the form of improved learning of academic content but also in the learning of scientific and life skills related to social organization and leadership. In our context, making use of the benefit of cooperative learning requires careful attention to the structuring, organizing, and evaluating of group activities that are a part of the larger context. Working productively in groups is a developmental process which can significantly enhance the individual student's level of learning. It is possible for the social context to be applied to assessment by having group oral presentations to the entire class after they have completed their practical and theoretical investigations.

47.6.3.4 The Historical Context

The historical context is the basis of the science story, as discussed, in depth, above. It will portray science in a more realistic and humanistic light and make learning science a more attractive endeavor for most students.

In view of the preceding discussion, history of science that is to be used for pedagogical purposes must tread a fine line through the pitfalls of extremes that could conceivably arise in interpreting history. Obviously, the origins of ideas must relate to the current understanding, which is the point from which history must, of necessity, be approached in education. A merely logical reconstruction of past events that produces pseudo-history must be avoided. History must be placed in its original context, while relating it to our current views, in a manner that respects the originators and portrays them in a fair and balanced way. The objective of accuracy or faithfulness to the historical record must, in turn, be balanced against the demands of a curriculum that limits the depth to which the history can be probed. It should be realized that the place of history is not only to make a conceptual point but also to introduce the humanistic element into the process of learning science. Portraying scientists as human beings and giving students the opportunity to become affectively involved in the story of science are worthy goals in themselves.

47.6.3.5 The Affective Context

The affective context is provided in numerous ways, initially by the story itself. Good stories are known to engage the emotions and enhance memory. The ability of the story to rouse emotions has already been discussed earlier in this chapter. While the affective context must be recognized, it is not a discrete context, as the social and practical contexts, for example, through aspects such as group work and hands-on activities, can play a notable role in generating student interest and contribute to

Fig. 47.3 A schema for incorporating stories in science teaching: the SDCA

increasing their motivation and level of participation. It is influenced further by the teacher, not only in her or his posing of questions, which may engender curiosity and wonder, but also in the telling of the story and the design and execution of the instructional activities.

47.6.3.6 Operationalizing the SDCA Framework

The story may be used as a starting point for a lesson, or it may be used in segments to motivate a series of student activities. Figure 47.3 (adapted from Klassen 2006) presents the process of integrating the science story into a lesson. The teacher supplies the story as a motivating, organizing, and contextualizing structure for the lesson. Students naturally bring their prior ideas, attitudes, knowledge, and experiences to the learning episode, which may be relevant to the concepts or abilities addressed. The presence of the various contexts will assure a heightened degree of engagement with the material of the lesson. The teacher contributes supervision in the role of a research leader, establishing the direction of the activities and acting as a resource for required information. After any successful lesson or series of lessons, students will have acquired various new ideas, attitudes, knowledge, and skills relating to the concepts or abilities that are being promoted by the lesson, which will influence the next lesson or series of lessons in an ongoing cycle.

Stories when used as door openers (Kubli 2005) are not used for the primary purpose of explanation but for the purposes of making the science concept being taught more memorable, reducing the distance between teacher and students and illuminating a particular point being made (Kubli 2005; Metz et al. 2007). Door-opening science stories provide “reasons for needing to know.” Another, perhaps more significant, purpose behind such stories is to raise questions or leave the student with unresolved problems or issues which form a significant part of the science material being taught. These questions arise not only from the story itself but also from the scientific issues and concepts that the science story contains. According to Gil-Pérez and coauthors (2002), questions play a central role in constructivist pedagogy. In their words, "[f]rom a scientific point of view it is essential to associate knowledge construction with problems: as Bachelard (1938) stresses, 'all knowledge is the answer to a question'" (p. 14). One would then expect that well-told stories would provide an incentive for students to raise a number of questions that they consider both interesting and important.

47.6.3.7 The Science Story as a Stand-Alone Implementation of the SDCA

The five contexts as identified in the SDCA are inherent in science instruction that incorporates well-designed stories in a well-conceived manner. The historical and theoretical contexts rest in the story itself. Since the science is elaborated within the story text, the practical context can be generated through the students' imagination, as shown in the Hadzigeorgiou and colleagues' (2012) research study. It has also already been demonstrated that the affective context emerges in the response to the story in the form of engagement, motivation, and long-term retention. Given that the told story raises questions in the students' minds and produces ongoing group discussion, the social context is developed within the learning environment, as well. The degree to which this is developed is largely in the hands of the teacher who determines in what kind of cooperative learning experiences his or her students will engage.

47.7 Conclusion

Theories of narrative are diverse and do not necessarily precipitate a set of common features of narrative. Because of the complexity and different understandings of narrative and story, a distillation of the common elements among various expositions of narrative theory does not result in a definition that can be applied practically in science education. The analysis of the literature and recent research reveals that the writing of good stories must focus on the structural elements of the story and include the relevant narrative features. The construction of such a list derives particularly useful insights from the narrative theory of Altman (2008) who emphasizes character and distinguishes elements relevant to the writing of a story. The story centers on the character who, in our case, is a real scientist, and the details are provided predominantly by the historical record. The consequential choices made by the scientist have the effect of raising human interest that, for example, stimulate the romantic understanding of students, as demonstrated in the study of Hadzigeorgiou and colleagues (2012). Such stories should also include an interwoven elaboration of the related science concepts. Provided that the story is well written, students can gain, from the told story alone, all the conceptual knowledge that they would have gleaned from conventional classroom instruction and demonstrate improved learning and better long-term retention of knowledge (Hadzigeorgiou et al. 2012). A story containing all the characteristics required to produce an effective contextual learning environment is also likely to rest in or produce the contexts essential to ensure sound science instruction. While the historical and affective contexts are always supplied by the story, teachers can opt to supply the theoretical, practical, and social elements separately from the story when they use it in the role of door opener to the instructional episode in conjunction with the questions that are naturally raised by the story.

Although the past decade has seen significant development in the definition and practical implementation of stories in the science classroom, the definitional structure of story that has been presented here requires wider dissemination and more diverse application. In order for research among various researchers to be comparable, there needs to be a standardized vehicle or framework of story structure and delivery, and the current chapter provides one such implementation method. Without a certain degree of standardization, it will not be possible to judge the effectiveness of the use of stories in science instruction nor to assess the anticipated progress in this research area.

Recent research on the effectiveness of stories in science instruction has already raised topics for further research; for example, the relative effectiveness of the story approach in different curricular contexts, in different national and cultural settings, and among different age groups of students needs to be investigated. The implementation process, of itself, raises additional research imperatives. Among these are the assessment of existing so-called stories, the writing of new science stories that correlate to specific curricula, and the collection and dissemination of such science stories that meet the criteria established in this chapter.

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Chapter 48
Philosophical Inquiry and Critical Thinking in Primary and Secondary Science Education

Tim Sprod

48.1 Introduction

This chapter considers two related, yet nonidentical, issues in science education: the role that can be played by philosophical inquiry and the place of critical (or indeed other types of) thinking.

The relationship between the two issues is clear, if you accept the claim by Lipman (1991) that philosophy is the discipline whose central concern is thinking. On this basis, he argues that philosophy should, therefore, be taught in all schools as a means of (among other things) improving the thinking of school students. Broadly accepting Lipman's claim, this chapter assesses its strength in relation to science teaching in schools.

This chapter starts with consideration of educational research into the nature of thinking, exploring the extent to which it is context bound, the problem of transfer across contexts and the nature of excellent thinking. Drawing on this work, I then turn attention to thinking within the context of science education. We shall see that the evidence suggests that present methods of science education, by and large, are not as good as they could be in developing the scientific thinking of students.

Next, I survey three programmes which have shown considerable promise in not only improving the scientific thinking of school students but also in having a positive impact on other desirable outcomes of science education: the Cognitive Acceleration through Science Education (CASE) programme, the Conceptual Challenge in Primary Science project and the Philosophy for Children (P4C) suite of approaches. Behind the success of these approaches seem to lie some common features: they provoke puzzlement or cognitive conflict; they depend heavily on a certain style of classroom discussion which is recognizably philosophical; they make metacognition explicit; and they have ways of encouraging transfer to other contexts.

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Finally, this chapter draws together the matters discussed, looks at some possible objections and considers the implications in four areas: for future research on effective programmes for scientific thinking and the other outcomes mentioned above, for investigating the impact of attributes of teacher on such programmes, for the provision of training for teachers in the delivery of effective programmes and on the need for the development of more materials to support teachers.

48.2 Thinking

48.2.1 Is Thinking General or Context Bound?

The first issue that arises is the generality of the good thinking at which we aim. Ever since Spearman (1927) introduced the notion of general intelligence *g*, there has been disagreement among theorists as to whether good thinking is a generic capacity (see, e.g. Ennis 1989, 1990), able to be turned to any discipline or whether good thinking is embedded in particular contexts or situations (McPeck 1990) so that a good thinker in science may not be able to think well in other disciplines. On the answer to this puzzle rests a more practical issue: should schools make space in the curriculum for separate 'thinking' classes, or should thinking be taught within each discipline? It should be noted that this is not an 'either-or' situation: it is possible that both are needed.

More recently, the discussion about whether thinking is domain specific or not has become more nuanced. No longer do theorists and experimental psychologists line up to defend either side. Rather, there seems to be more agreement that there is truth in both accounts. In a recent survey, Adey and colleagues (2007, p. 78) state that '[w]e can find no support in the current psychological literature for either of these extreme views… What emerges from the vast literature that exists on the structure of general abilities [is] that both general and specialised processes are interwoven in the human mind'. Despite this convergence, there still exists considerable difference as to the nature of these two and of the ways in which they interact. Perkins and Saloman conclude:

> The approach that now seems warranted calls for the intimate intermingling of generality and context-specificity in instruction. … We forecast that wider-scale efforts to join subject-matter instruction and the teaching of thinking will be one of the exciting stories of the next decade of research and educational innovation. (Perkins and Saloman 1989, p. 24)

To claim that there is such a thing as general thinking ability (or general cognitive ability, or intelligence) is not to deny that all thinking is contextual, in the sense that it must take place in some context, using some content. Rather, it is to claim that there is a core set of capacities and dispositions which have the potential to be applied across a large variety of contexts. These general abilities are then augmented by capacities that are more specialised to particular contexts and applications.

Moreover, there is growing agreement that complex thinking in a domain requires a reasonable grasp of content (Bailin 1998; Paul and Elder 1999; Willingham 2007).

In relation to education in science, two questions arise that will be addressed later in this chapter. Firstly, there is the question of transfer. If students develop the capacity to use a certain type of thinking well in one context, how easily can they transfer that capacity to different contexts? If such transfer does not happen spontaneously, then what are the conditions and classroom activities that will enhance such transfer? Secondly, there is the issue of plasticity. Do individuals have a genetically determined capacity for good thinking, or is their ability susceptible to environmental influences, including educational ones? Does the development of general cognitive capacities run according to a set timetable, or can educational interventions speed up their acquisition?

Before we turn our attention to these questions, we need to survey the ways in which good thinking has been characterised.

48.2.2 *What Is Thinking, and What Makes It Good?*

If we are aiming to improve the scientific thinking of school students, then we had better have a clear idea of the target. This is, however, less easy than it might seem on the surface, since there is considerable disagreement about what to call such thinking, let alone of what it consists. Lipman (1991), for example, in a chapter interestingly titled ‘The cornucopia of cognitive performance’, talks variously of higher-order thinking, good thinking and excellent thinking.

The title to this chapter has used what is probably the most popular name: critical thinking. The popularity of this name probably stems from John Passmore’s highly influential article ‘On teaching to be critical’ (1967). Yet, within what might be called the critical thinking movement, there exists quite a bit of internal disagreement about how exactly ‘critical thinking’ should be characterised, particularly at the level of specific characteristics a critical thinker has.[1] Despite this diversity, different theorists often mention the same or similar elements, differing more on their arrangement or interrelations. A common thread that runs through many of these accounts is a distinction between capacities (or skills, or capabilities)[2] and dispositions (or habits, or traits). The former refer to cognitive moves that can be made, and the latter to the desire to make them. It is commonly claimed that a good thinker needs both.

The label critical thinking, however, has been questioned for an overly rational emphasis (de Bono 1986). Some of the critical thinking theorists – see, for example,

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[1] See, for example, Ennis (1987), Paul and Elder (2007), Resnick (1987), and Siegel (1990).

[2] Some theorists object to the term ‘thinking skills’ (e.g. Hart (1993); see also Lipman (1991, pp. 78–80),where he discusses Hart), as reducing a complex, interwoven human activity to a series of atomistic technical skills. I will not enter into this discussion: in what follows, I will use ‘skills’, ‘capacities’, ‘capabilities’ and so on interchangeably.

Siegel (1990) – claim that critical thinking is a very wide concept, including all cognition and quite a bit beyond, such as the affective. Others prefer to confine the adjective 'critical' to the rational, convergent type of thinking and to refer to the more imaginative, divergent type as creative thinking (Swartz et al. 1998). In these accounts, it can seem as though there are two distinct types of thinking. Lipman (1991), whose favoured term is higher-order thinking, prefers to talk about the critical and creative *aspects* of higher-order thinking, saying 'there is no creative thinking that is not shot through with critical judgments, just as there is no critical judgment that is not shot through with creative judgments' (p. 193). He also added a further aspect – caring thinking (Lipman 1995) – to acknowledge the important role of the emotions in higher-order thinking. In my own work, I argue for the term 'reasonableness' and identify five aspects: critical, creative, committed (roughly equivalent to Lipman's 'caring'), contextual and embodied thinking (Sprod 2001).

Lipman (1991, pp. 50–51) makes the point that good thinking is contextual and nonhierarchical. By this, he means that skills which may seem to be low level in one context may be crucial in another. Further, a good thinker not only has the capacity to use skilful thinking and the disposition to do so but also must have the judgement and discrimination to recognise the appropriate moment to call upon each skill. Using the analogy of the carpenter, Lipman (1991) comments that it is not enough to know how to wield a hammer and a plane skilfully: the judgement to know which situations require a hammer, and which a plane, is also essential. Ritchhart and Perkins (2000, p. 30) analyse the dispositions needed to think well as having three aspects – the inclination to think well, the ability to do so and the sensitivity to know where and when to use those abilities – making what appears to be the same point in somewhat different language.

Further, Paul and Elder (2007) point out that thinking which is good by technical standards (pragmatically successful) can be 'intellectually flawed' if not grounded in 'fair-mindedness and intellectual integrity'. The former may merely involve 'the technical perfecting of isolated cognitive skills' (Lipman 1991, p. 51).

Characterising accurately the nature of thinking is well beyond the scope of this chapter, but the foregoing discussion has highlighted that, if we have the aim of teaching good thinking in science, we need to be aware that the sort of thinking we are seeking to encourage and inculcate is quite a complex set of capabilities and dispositions, backed by sound judgement. It is now time to turn our attention to a matter that merges the concerns of these last two sections: the nature of scientific thinking.

48.2.3 Scientific Thinking

We have seen above that there are differences of opinion as to whether good scientific thinking is good general thinking applied to science[3] or is a distinctive type of

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[3] Huxley (1894) is often quoted giving his opinion that science is 'nothing but trained and organised common sense'. See also Royer (1987).

thinking.[4] Once again, many commentators seem to be converging on a view that scientists utilise many general thinking skills and dispositions but also have developed more specific ones that either relate more to scientific contexts or have been developed to a greater and more precise degree by scientists.[5]

Adey and colleagues (2007) make a powerful case that we can consider scientific (and indeed, all) thinking as a combination of central, shared competence (which they call general intelligence *g*) and a suite of subsidiary competences that are much more subject specific. Exactly how these are related is less certain, and they survey a number of models. We should note in passing here that it is hard to see how a sharp distinction can be drawn between the central and the subsidiary elements of thinking. Are some of them merely more sophisticated versions of general thinking (e.g. ability to discriminate), while others are rather different from any skills of general thinking (e.g. statistical inference)? Is there a difference in kind that separates the drawing of distinctions between characters in literary analysis and distinguishing between possible confounding variables in science?

Research scientists at the cutting edge have clearly developed their scientific thinking to a high degree. It is also clear that the precise mix of capacities used in expert scientific thinking will vary from one field to another within the sciences – the development of these subsidiary competences depends heavily on the requirements of the field.

Much work has been done on the acquisition of scientific thinking by children as they mature and are educated,[6] yet only a small proportion of it extends beyond the middle years of schooling. I am unaware of any study that traces in detail the development of scientific thinking in the transition from senior secondary school student to fully fledged scientist (though there are studies that take single-stage 'snapshots', particularly in early undergraduate years). Indeed, such a study would be a major one, requiring a very long-term longitudinal design. Moreover, much of the research focuses on, as Zimmerman (2007) puts it, 'the three major cognitive components of scientific discovery: Searching for hypotheses, searching for experiments (i.e., data or evidence from experiments or investigations more generally), and evidence evaluation'. Thus, the model of scientific thinking here is quite narrow, being based on a singular conception of The Scientific Method.[7] Nor is it clear that searching for

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[4] Wolpert (1992) argues that 'science involves a special mode of thought and is unnatural for two main reasons … Firstly, the world just is not constructed on a common-sensical basis. This means that 'natural' thinking – ordinary, day-to-day common sense – will never give an understanding about the nature of science.… Secondly, doing science requires a conscious awareness of the pitfalls of 'natural' thinking. For common sense is prone to error when applied to problems requiring rigorous and quantitative thinking ….'

[5] See, for example, Adey et al. (2007), Adey (2006), Bailin (2002), Ennis (1990), Gazzard (1993), McPeck (1990), Norris (1992), Paul and Elder (2007), Perkins and Saloman (1989), Siegel (1989), and Siegel (1991).

[6] See, for example, Kuhn et al. (1988), Kuhn and Pearsall (2000), Zimmerman (2000), and Zimmerman (2007). The latter is a recent, comprehensive survey of such work.

[7] Many school science texts refer to what I am calling here 'The Scientific Method', which takes experimental work with tightly controlled variables as the model for all science (Lederman and Lederman 2004). See further discussion in Sprod (2011, pp. 4, 66).

possible explanations, seeking data to test them and evaluating the evidence adduced are skills that apply solely to science.

Searching ERIC with the descriptors 'science education' and 'thinking skills' returns 649 matches. Using the above terms with a variety of words derived from 'category', 'type' and 'taxonomy' revealed no empirical studies that tried to categorise the different scientific thinking skills that students develop through their science education. There were, however, quite a few studies[8] that took a particular thinking skill – or, occasionally, disposition – and studied the ways in which some intervention may strengthen it. Hence, researchers and teachers clearly have some typology of scientific thinking on which they draw.

The most comprehensive typology of science thinking skills that I could discover on the Internet (Table 48.1) is found on the Boston Museum of Science (2001) site. The single source that they quote for their list is the Californian State Department of Education (1990) document 'Science Framework for California Public Schools' (see Table 48.2). The members of the team who wrote the document appear to have compiled this list by drawing on their own experience and ideas, judging by the lack of references to any papers which have developed a typology of science thinking skills.

Again, a perusal of the lists in Tables 48.1 and 48.2 leads one to wonder if any or, at the very least, many of these skills are unique to science. Certainly, in their more developed guises, such skills as categorisation may become much more sophisticated and specialised than their everyday counterparts, but it is hard to see how their roots can be anywhere other than in more general thinking skills that can be applied across many domains. There appears to be a need for empirical work to delineate the thinking skills that scientists actually use in their work and to explore how they develop these skills through their education, right up to the level of employment as a scientist.

Hence, we may well feel that children's scientific thinking in the early years of education leans heavily on those shared competencies that are utilised in all the disciplines and that as they grow older and become more educated in science, not only will their general competence increase, but they will also start to develop some of the more context-dependent thinking competencies that apply more specifically to science. Science education, then, ought to have the dual roles both of strengthening the general ability to think well (a role it ought to share with the other disciplines) and of developing those modes of thinking which have more specific application in science.

48.2.4 Developing Scientific Thinking in Schools

In the light of compelling evidence (see, e.g. Lyons (2006), Pell and Jarvis (2001), Tytler (2007)) that students find school science boring, largely requiring the regurgitation of facts, there have been calls, as Tytler puts it, to 'reimagine' science

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[8] For example, Venville and Dawson (2010) on argumentation and informal reasoning, Settelmaier (2003) on ethical dilemmas, May et al. (2006) on analogical reasoning and Vieira et al. (2011) on conceptual clarification.

Table 48.1 Science thinking skills typology (Adapted from Boston Museum of Science (2001))

Seeing the unseen – observation
Becoming active observers
Using all senses in making observations
Developing observational skills
Awareness of strengths and limitations of observations
Using tools to extend senses
Transferring observational skills to other contexts
Finding the pattern – classification
Observing, comparing and sorting objects and phenomena in meaningful ways
Recognising that systems for organising and classifying objects and phenomena reveal underlying meaning
Using organised material collections to answer questions and solve problems
Searching for the 'hidden' meaning in objects and phenomena
Making models – description
Recognising the presence and value of models
Becoming familiar with several types of models: physical models, conceptual models, mathematical models and computer simulations
Practising four specific science thinking skills associated with making and using models:
Recognising the similarity between models and the things they represent
Assessing the strengths and limitations of models in explaining and predicting the behaviour of the objects or phenomena they represent
Using models to raise questions, communicate ideas and test hypotheses in many different contexts
Creating models to explain things they cannot be observed directly
Testing the theory – experimentation
Formulating and testing ideas about the world
Asking questions and generating ideas
Formulating hypotheses
Gathering and weighing evidence
Using instruments to design experiments
Recording and interpreting data
Drawing conclusions
Being aware of what it means to experiment
Transferring scientific habits of mind (curiosity, respect for evidence, scepticism and open-mindedness) to other settings
Participating in ongoing scientific research
Putting it to work – application
[No list of component skills given]
Playing with ideas – imagination
[No list of component skills given]

education. One of the common phrases used in these calls is to make science lessons more 'minds-on' (Sprod 2011). Such a characterisation builds on a broad-brush history of science education which sees the early approach as 'ears-and-eyes-on' (lectures and demonstration experiments), to which, from the mid-twentieth century, was added 'hands-on' (student experimentation). Towards the end of the last

Table 48.2 List of science thinking skills adapted from the California Department of Education's *Science Framework for California Public Schools* (1990, p. 151)

Observing: the scientific thinking process from which fundamental patterns of the world are construed
Communicating: the scientific thinking process that conveys ideas through social interchanges
Comparing: the scientific thinking process that deals with concepts of similarities and differences
Ordering: the scientific thinking process that deals with patterns of sequence and seriation
Categorising: the scientific thinking process that deals with patterns of groups and classes
Relating: the scientific thinking process that deals with principles concerning interactions
Inferring: the scientific thinking process that deals with ideas that are remote in time and space
Applying: the scientific thinking process by which we use knowledge

century, in the light of more research (e.g. Jurd 2004; Abrahams and Millar 2008) that showed much practical work in schools was unaccompanied by little thought about the science or even the purpose of the experiment, the phrase 'minds-on' started to appear more frequently. Indeed, in much of the literature, the two latter phrases are often conjoined into 'hands-on, minds-on' (e.g. in Andre (1997), Jegede and Taylor (1995), and Pedersen and McCurdy (1992)).

So, even granted that we have some reasonably shared idea of what constitutes good scientific thinking, we can ask whether students learn this well by following a traditional science education or whether some new or different ('minds-on') pedagogical approach needs to be added to science curricula. There is quite a bit of evidence that traditional methods are not enough (Kuhn 1999), though most of this evidence is in the form of studies that show some particular intervention has a positive effect on scientific thinking skills over and above that of traditional methods.[9] The implication, then, is that those traditional methods are failing to make the most of the possibilities for developing scientific thinking.

Many of these studies are quite small scale and carried out over a relatively short time frame. Hence, methodological questions arise about experimenter effects, confounding variables, generalisability to other contexts and so on. Moreover, it is not clear that all researchers are using key terms such as 'direct instruction', 'transfer', 'inquiry method', 'scaffolding' and 'conventional teaching' in the same sense (Zimmerman 2007, p. 215), making comparisons between studies difficult.

However, perhaps the major shortcoming of small-scale studies is that they do not deal with the most important question: even granted that some statistically significant effects can be demonstrated after intervention, are these effects long lasting? In other words, do they transfer to other contexts at much later times? Only if it can be demonstrated that certain changes to teaching and learning make a real difference to children's abilities over significant timescales and, in novel situations, will there be a strong case for making those changes.

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[9] For example, Balcaen (2008), Cavagnetto et al. (2011), Choi et al. (2010), Dawson (2010), Hand and Choi (2010), Lee and She (2010), Miri et al. (2007), Mitchell (2010), Pithers and Soden (2000), Sadler (2004), She and Liao (2010), Songer et al. (2009), and Sprod (1998). See also note 8.

There are, as mentioned, many suggestions as to what changes to scientific education need to be made. Many of these form the subject of other chapters in this handbook. In the next section of this chapter, I will survey some approaches[10] that can make claims to have demonstrated lasting changes in reasoning. As we shall see, scientific reasoning is not their sole target.

48.3 Philosophical Inquiry and Science Education

The three programmes on which this section will focus are as follows: Cognitive Acceleration through Science Education (Adey et al. 1995) and its related spin-offs; the Conceptual Challenge in Primary Science program; and approaches derived from Philosophy for Children and its methodology, the community of inquiry (Lipman et al. 1980). As stated in the introduction, programmes designed for science classes in schools which involve some form of philosophical inquiry can have many more aims that merely improve the scientific thinking of students. Nevertheless, given Lipman's claim that philosophy is the natural home of thinking, such programmes will have as one of their central aims the expansion and augmentation of students' ability to think scientifically.

48.3.1 Cognitive Acceleration Through Science Education (CASE)

If educational managers require solid empirical evidence before introducing changes to curricula, then the CASE project is compelling. CASE and the cognitive acceleration (CA) projects that grew out of it[11] have been among the most intensively studied innovations in science education,[12] with a most impressive track record.

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[10] Unfortunately, the survey that follows will, due to my linguistic limitations, be largely limited to work published in English. Certainly, important work has been carried out in other languages – see, for example, Vieira et al. (2010). There are also many projects in science education that include in their aims the improvement of scientific thinking but for which, to my knowledge, no empirical research has been done to test the claims – for example, Aikenhead's *Logical Reasoning in Science and Technology* (Aikenhead 1990).

[11] 'Other members of the growing family include CAME (in mathematics for junior secondary), PCAME (mathematics for Years 5 and 6, ages 9–11 years), *Let's Think!* (science/general reasoning for Year 1, 5–6 year olds), *Let's Think through Science!* (for Years 3 and 4, 7–9 years) – all developed at King's College, London – and CATE (technology), and ARTS (junior secondary music, drama, and visual arts)' developed elsewhere (Adey 2005).

[12] Adey (1997, 2004, 2005), Adey et al. (2002), Adey and Shayer (1990, 1994), and Shayer and Adey (1993)

The original CASE project involved using one lower secondary science class every second week for the first two secondary school years in activities based around Piagetian-based operations such as control and exclusion of variables, ratio and proportion, compensation and equilibrium, correlation, probability, classification and formal models. In other words, the major focus was not on any particular scientific content,[13] but rather on some aspect of scientific thinking. A typical lesson moves from a ‘concrete preparation’, where new equipment and vocabulary are introduced, through an activity designed to create cognitive conflict in their students’ heads, onto the core phase where students strive jointly to construct a satisfactory explanation, paying attention to the thinking that is going on (metacognition) and seeking to apply their insights to other similar situations, all under the guidance of the teacher.

The major claim to arise from the project is that it is possible to improve the thinking skills of students significantly through this sort of programme and that the effects of these improvements can still be measured 3 years after the intervention finishes, by their effect on student performance in external examinations – not only in science but also in mathematics and English GCSEs. This is long-term, far transfer (Adey and Shayer 1994).

There are two aspects which need attention here. The first is the theoretical underpinnings of the project, and the second is the key factors which the researchers have identified as being vital to the programme’s effects.

CASE’s theoretical base lies in psychology rather than philosophy. The initial theoretical driver of the project was Piagetian stage theory. The materials were designed to accelerate the passage of students who used them through the stages, by provoking cognitive conflict and assisting assimilation. Specifically, it was thought that students could be assisted to move from the concrete operational to the formal operational stage; hence, the project was targeted at students around the age of 12 (the first 2 years of secondary school).

Drawing on the work of Vygotsky (1962) on the social nature of cognitive development and some little recognised work of Piaget and his collaborators on social interaction (Adey et al. 2007), the means for accelerating cognitive development were devised, trialled extensively and assessed in a multistage longitudinal study.

The thoughts of the principal investigators in the suite of CA projects on why the programmes work will be of primary interest to readers of this handbook.

Firstly, we have to address the question, raised in 2.1, of transfer. Does CASE really demonstrate long-term, far transfer of effects on scientific thinking, when much of the literature points to the difficulty of doing so? Adey (2006, p. 2) says ‘we can answer a clear ‘yes’: stimulating higher order thinking in science improves students’ general intellectual ability across the board’. Adey et al. argue that while

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[13] Of course, each lesson does contain content, so that control of variables might be studied through consideration of the effects of the length, width and material of a pipe on the pitch of the note produced by blowing across it, or probability via flipping coins.

general abilities are acquired and/or practised in particular contexts, on specific content, which might be thought to limit their general application, by

> mining more deeply into the insights and models of developmental psychology and paying attention to the general intellectual processors of the mind (both 'executive' and 'central') … (Adey et al. 2007, p. 92)

we can create conditions under which transfer is much more likely. Thus,

> moving along the scale of "subject matter versus general ability" towards the direction of developing general abilities actually opens up broad opportunities for raising levels of traditional academic achievement. … you have to have both concrete content and reflective abstraction. If you teach the specifics with abstraction in mind, the general is learned, but if you try to teach the general directly, the specifics often are not learned. (Adey et al. 2007, p. 92)

These observations may give us cause to wonder: is using the CA materials necessary to get the gains their research has shown, or are there essential features of the CA approach which can be used to design other programmes or to influence teaching methodologies more generally? If so, what are the key features? In a number of articles, the team has identified these factors, calling them the pillars of CA. Here is one characterisation of the pillars:

1. *Cognitive Conflict.* Piaget suggested that one of the mechanisms by which cognition develops is through a challenge to existing cognitive structures by experiences which make demands somewhat beyond the child's current processing capability. The same idea is encompassed by Vygotsky's zone of proximal development ('the only good learning is that which is advance of development'). CASE activities are designed to provide such challenge, in scientific contexts, on a slope of increasing difficulty such that, at some point, students of different abilities all encounter cognitive conflict.
2. *Social Construction.* Both Piaget and Vygotsky stressed the role of social interaction in cognitive development, although it is Vygotsky's claim that 'ideas appear first in the social space and then become internalised by the individual' that is best remembered. CASE pedagogy emphasises the importance of collaborative learning in the class, with groups of students interacting with one another, positive argument and critical questioning encouraged and every student's contribution valued.
3. *Metacognition.* Another notion central to the Piagetian model of cognitive development, especially for the emergence of formal operations, is 'reflective abstraction', the idea that the individual reaches a higher level of thinking by reflecting on their own thinking. The Vygotskyan notion that language acts as a mediator of learning also suggests that putting thoughts into words (the conscious explication of thought) is a powerful driver of cognitive development. CASE teachers encourage their students to explain what they are thinking, what they find difficult, what they have learned, what mistakes they have made and how they corrected them (Adey 2006, pp 2–3).

To these three pillars, they have elsewhere added 'two subsidiary pillars (*concrete preparation*, introducing the topic, and *bridging* – showing how the same sort of thinking can be used elsewhere)' (Adey 2005).

One might wonder, at this point, whether the domain through which such cognitive acceleration is delivered needs to be science and, if not, whether there are advantages in doing it through science. Again the CA team has addressed such thoughts. Adey says that, while 'in principle there is no reason why such an approach should not be taken through any subject domain' (Adey 2006), 'science in schools is a domain which may be peculiarly well adapted for the development of, at least, a general understanding of problem solving which would be expected to be useful across both school domains and everyday life' (Adey 1997). This is, in part, because 'the schemata of formal operations described by Inhelder and Piaget (1958) (control and exclusion of variables, proportionality, classification systems, equilibrium, and the others) have a very science-y look to them' (Adey 2006).

Indeed, the CA team have identified several other programmes which seem to fit their pillars well[14] and which have a track record of improving cognitive functioning:

> Long ago Vygotsky claimed that all learning in school from the early years onward should be directed as much to children's cognitive development as to their subject learning (Shayer 2002). The transfer evidence from Cognitive Acceleration, Instrumental Enrichment, and Philosophy for Children suggests that the technology is now being developed to make that a practical and realisable aim. Each of these interventions clearly stimulates something much deeper than domain specific systems, and that 'something', we would claim, is general mental ability, or general intelligence. (Adey et al. 2007, p. 92)

As noted previously, one of the great strengths of CASE and related programmes is that there are a number of longitudinal studies demonstrating their efficacy in long-term, far transfer. As Adey et al. (2007) themselves comment, it is a pity that other promising educational programmes have not been the subject of similar research, particularly in terms of attempting to measure whether the effects seen in short-term studies are long lasting. Clearly, large longitudinal studies are not easy to carry out. Issues of funding, continuity of staffing and the like have been discussed in a special issue of *Research in Science Education* (vol. 35, no. 1, 2005).

Longitudinal studies also have the disadvantage, as Tytler and Peterson (2005) put it, that 'there are many points at which we wish we had gathered different or better data at the earlier stages'. For example, Adey (1994, personal communication) began to wish that the CASE team had collected more data on the use and type of discussion in CASE classes, as they realised that this second pillar was one of the more powerful features explaining the effects of the intervention.

Of interest, while considering longitudinal studies that have demonstrated robust long-term effects, is the comparison of CASE with Novak and Musonda's study of science concept learning, based on the theories of Ausubel (Novak and Musonda 1991; Novak 2005). Tytler et al. (2005) comment that '[t]he success of both interventions, situated as they are in quite different theories, gives pause for thought. They perhaps suggest the existence of common and significant principles underlying both Piagetian and Ausubelian theories'. Piaget was concerned

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[14] There are other programmes, not identified by the CA team, that also share many of these features and have been shown to have positive effects, for example, work by Carol McGuinness and colleagues in Northern Ireland (McGuinness 2006).

with the structures of thought, Ausubel with acquisition of concepts. I would suggest that the link is that both studies also draw heavily on Vygotskyan ideas on how children internalise both the capacities of thought and concepts through social interaction.

48.3.2 The Conceptual Challenge in Primary Science Project

A second project that can be seen to share the Cognitive Acceleration pillars referred to above is the *Conceptual Challenge in Primary Science* project, originating at Oxford Brooks University in the United Kingdom (Mant et al. 2007; Wilson et al. 2004).

The four emphases in this project are:

1. Increased time spent in discussion of scientific ideas
2. An increased emphasis on the encouragement of higher order thinking
3. More practical work and investigations
4. More focused and purposeful recording by pupils, less writing (Mant et al. 2007, p. 1712)

In the first three, we can recognise the pillars social construction, metacognition and the opportunity for cognitive conflict respectively. Two key teachers from each of 16 primary schools participated in ongoing professional development sessions run by the researchers that concentrated on developing 'cognitively challenging, practical science lessons with plenty of space for thinking and discussion' (Mant et al. 2007, p. 1712). One of the major innovations was the introduction of 'Bright Ideas Time' discussion slots based on a discussion prompt (more details of the methods are to be found in Wilson and Mant 2006). The time to include more practical work and discussion sessions came largely from taking a close look at how much writing and recording students were required to do so that 'teachers focused on the *purpose* of recording by the pupils, so that although less was demanded it was of a higher quality' (Mant et al. 2007, p. 1716, emphasis added).

As with the CASE research, the main measure of effectiveness of the method was to use an externally set and marked test. In this project, the test was the UK's national science assessment test, and the relevant measure was the proportion of students achieving level 5 on the test. Specifically, the project found that, when matched against similar schools, the 16 experimental schools recorded a significantly greater average increase in level 5s of 11.8 %, against 2.0 % in the control schools. Semi-structured focus group interviews with project students showed that they rated the lessons as more challenging, active, collaborative and requiring more thinking.

In more recent research, the Oxford Brookes group has polled over 5,000 12-year-old students to identify exemplary science teachers, measured by the degree to which the students reported being engaged and motivated by science lessons. Through questionnaires administered to the students of those teachers (Wilson and Mant 2011a) and through group interviews with those teachers

(Wilson and Mant 2011b), they sought to determine the teacher-mediated factors that make science education effective. The four factors that both students and teachers agreed upon make interesting reading in the context of the concerns of this chapter: they are the use of discussion, an emphasis on thinking, more student practical work and the contextualisation of science in terms of students' lives (Wilson and Mant 2011b, p. 118).

48.3.3 Philosophy for Children (P4C) and the Community of Inquiry (CoI)

Philosophy for Children had its genesis in the work of Lipman et al. (1980). The basic structure of the programme, as Lipman initially conceived it, is a series of novels accompanied by teacher's manuals, delivered in the classroom through a community of inquiry. The initial novel, *Harry Stottlemeier's Discovery* (Lipman 1974), had a 'spine' concerned with formal syllogistic logic, though plenty of other philosophical puzzles were also woven into it. These were 'unpacked' for the teachers through explanations, discussion plans and exercises in the manual (Lipman and Sharp 1975).[15]

The community of inquiry is a specific type of whole-class discussion. Lipman (1991) identifies five stages: (I) reading a portion of the story; (II) gathering questions from the students as a means of constructing an agenda; (III) the students taking responsibility for discussion; (IV) the teacher taking responsibility for prompting the discussion to be rigorous, rich and meaningful; and (V) follow up activities.[16]

It is worth commenting on these stages. In (I), the stories have been written to contain what my son Liam called 'philosoful' hooks (Sprod 1993). However, instead of the teacher identifying them and asking the students questions about them, it is the students who set the agenda for the discussion to follow by asking questions about those incidents in the story that puzzle or interest them. In this way, the community of inquiry starts in a narrative about children which supplies the concrete situation (CA's first subsidiary pillar) and identifies those ideas that have caused cognitive conflict (CA's first major pillar) for the students – especially when they choose from the questions asked one that most students want to try to answer.

Stages (III) and (IV), which interleave, use the whole-class discussion as a means of providing social construction of concepts, thinking skills and dispositions and

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[15] It is worth noting at this point that the Philosophy for Children field has diversified considerably since Lipman's model was devised – so much so, in fact, that different theorists and practitioners have suggested broader names, such as philosophy with children (Murris 2008), philosophy in schools (Hand and Winstanley 2009) and dialogical philosophy (Stone 2011). Moreover, there has been an explosion in classroom materials that use many different materials instead of Lipman's purpose-written novels, such as specially written short stories (e.g. Cam 1997; Worley 2011), picture books (e.g. Murris 1992; Sprod 1993; Wartenberg 2009) and film (e.g. Wartenberg 2007).

[16] The discussion that follows draws in part on a much fuller discussion of the community of inquiry in Sprod (2001), Chaps. 7, 8, and 9, especially pp. 183–189.

many more elements (CA's second major pillar). The teacher's role is vital[17]: to keep the discussion in the zone of proximal development. If the discussion loses its edge of inquiry, then the students fall below the ZPD (Gardner 1996), yet it could also lose the students by making too great a demand on their thinking so that they cannot follow.

The community of inquiry handles the third of CA's major pillars, and the second minor one, in two ways. At times, the metacognition and bridging can be tacit. For example, the teacher may label a certain student's idea as an assumption, without exploring explicitly with the students what an assumption is. At other times, though, the discussion can turn its focus on the tools of thinking being used (Sprod 2001, pp. 190–191). Using assumptions again as the example, the teacher may ask students to consider what the role of assumptions is or why it matters that we identify assumptions. Similarly, for bridging, the teacher or a student may introduce another situation when the analysis just completed can also be applied, or the teacher can ask students explicitly to think about the analysis and to find other areas in which to apply it.

From this brief outline of the key features of Philosophy for Children and the community of inquiry, we can see that it exhibits the features identified by Adey (2005) for effective cognitive acceleration. It is worth, however, considering the relation of the CA programmes to P4C in a little more detail.

One of the rich and interesting comments by Adey and colleagues, when considering the relation of CA to other programmes, is the following:

> Lipman's [sic] Philosophy for Children has shown good transfer effects with a general population but is essentially a pragmatic, under-theorised approach. Both [it and Feuerstein's Instrumental Enrichment] face the practical problem in school curriculum terms of requiring scheduled time for "thinking lessons".
>
> We suggest that the content-based approach offers more promise for large scale implementation …. (Adey et al. 2007, p. 92)

In the first sentence above, Adey and his colleagues, as psychologists themselves, clearly have psychological theory in mind when they say Philosophy for Children is under-theorised. Anybody who has seriously read Lipman's magnum opus, *Thinking in Education* (1991), as well as a host of other theoretical texts in the field,[18] would be loath to say that P4C is *philosophically* under-theorised. Indeed, I would claim that, while the CASE authors may have theorised the underlying processes of thinking in a more thorough psychological way, P4C writers have a better theoretical grasp on the philosophical bases of rigorous whole-class discussions. Clearly, each camp can learn from the other.

The second claim is that P4C requires separate 'thinking lessons'. If philosophy is not considered a central subject in a good education (philosophy commonly does not appear in curricula in the English-speaking world, but it does have a place in many other countries), then it is true that philosophical communities of inquiry may

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[17] See Sprod (2001), Chap. 3, for a philosophical treatment of this 'pedagogical action'.

[18] For example, Hand and Winstanley (2009), Lipman (1993), Lipman et al. (1980), Matthews (1982, 1994); McCall (2009), Pritchard (1996), Splitter and Sharp (1995), and Sprod (2001).

be seen as extra add-ons to the curriculum: separate thinking lessons. Even so, they would still be ‘content based’ in the sense that Adey et al. use – the content being philosophy.

Nevertheless, there is a good point here: do we need more subjects in an already crowded curriculum? Where do we make room for separate thinking – or philosophy – lessons? As the CA programme recognises, it might be better to infuse the subjects already taught with thinking.[19] Given the specific focus of this handbook, then the case for scientific communities of inquiry needs to be explored. I will do so below.

Before doing that, though, let us look at the evidence for the effectiveness of P4C, both in terms of improving thinking and in other areas. Over many years, both theorists and teachers in P4C have sought to demonstrate empirically the effects of the programme. Anecdotal evidence is abundant, but not compelling, especially to outsiders. While many studies have been carried out,[20] most are small scale and often poorly designed. Hence, despite the near unanimity of their findings of improvement, their reliability can be questioned. A meta-analysis of 18 of the most robust of these studies (Garcia-Moriyon et al. 2004) found that there was consistent evidence of improvement in reasoning, with a mean effect size of 0.58 (p<.001). However, in no case was the intervention more than 1 year, and no longitudinal data were collected to test for retention of the effect.

Since then, a well-designed, longitudinal study has been carried out in Scotland. Prior to the intervention, a survey of ten previous studies, considered to be rigorous in methodology, found a mean effect size of 0.43, ‘indicating a consistent moderate positive effect for P4C on a wide range of outcome measures’ (Trickey and Topping 2004). Subsequent reports on the intervention (1 h per week over 16 months) found the groups exposed to Philosophy for Children had ‘significant standardized gains in verbal and also in non-verbal and quantitative aspects of reasoning’ (Topping and Trickey 2007a) and exhibited ‘increased use of open-ended questions by the teacher, increased participation of pupils in classroom dialogue, and improved pupil reasoning in justification of opinions’ (Topping and Trickey 2007c), while there was a significant gain in ‘self-esteem as a learner, significant reduction in dependency and anxiety and of greater self-confidence’ (Trickey and Topping 2006). The control groups showed no significant changes on any of these measures. Following up 2 years later, they found that ‘[t]he significant pre-post cognitive ability gains in the experimental group in primary school were maintained towards the end of their second year of secondary school’ (Topping and Trickey 2007b).

Thus, there is now robust evidence that P4C has a similar positive effect on reasoning and long-term transfer to CASE. There are some differences. Trickey and Topping did not measure effects on external examination results, but CASE did not look at the wider range of outcomes, such as classroom interaction and socio-emotional factors. The CA programmes focus fairly narrowly on cognitive and subject-specific factors,

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[19] One might also add ethics.

[20] Citations for 74 empirical studies can be found at <http://cehs.montclair.edu/academic/iapc/research.shtml>.

while the P4C approach encompasses a much wider range of factors (as we shall see in the next section). Reasoning is not the only target.

So far, we have been considering the application of the community of inquiry methodology with philosophy as its primary focus. Let us look at the idea of bringing science to the centre.

48.3.4 The Scientific Community of Inquiry

A distinction has been made earlier between the Philosophy for Children programme – whether this be Lipman's original set of eight novels[21] or some modification using other materials,[22] but which retains philosophy as the central content focus – and the teaching methodology employed, the community of inquiry.

As a pedagogical technique, the community of inquiry (CoI) can be used with other subject areas as the core content. So, we can talk about an historical CoI, an artistic CoI, a mathematical CoI, an ethical CoI and so on. However, due to the nature of the questioning and inquiry that goes on in a CoI, many (e.g. Cam 1995, pp. 14–15; Splitter and Sharp 1995, p. 24) have argued that the CoI inevitably leads into an exploration of the philosophical roots of the central discipline, at least at times. So, as we shall see, it will prove with the scientific community of inquiry.

Compared to the wealth of materials developed for communities of philosophical inquiry, there has not, to date, been a great deal of work done on communities of inquiry in the other disciplinary areas, including science.[23] Given that Lipman derives the phrase community of inquiry from Peirce (Lipman 1991, p. 15), and that Peirce used the phrase (in *The Fixation of Belief*) in relation to inquiry within the community of scientists (Peirce 1955, pp. 5–22), this is perhaps a little puzzling.

Gazzard (1993) contends that 'Philosophy is an integral part of every discipline and therefore similarly should be an integral part of its instruction … science more than any other discipline need the complement of philosophy … for it is scientific knowledge more than most which is accepted by the general population as being true' (p. 619). To support her view, she points to the generative and fallibilistic nature of scientific knowledge, contrasting this with the teaching of science as revealed truth. Hence, science teaching should include consideration of the epistemology and methodology of science. Through the use of a scientific

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[21] The Lipman novels, with the year group for which they are intended in brackets, are the following: Elfie (1), Kio & Gus (2–3), Pixie (3–4), Nous (4–6), Harry Stottlemeier's Discovery (5–6), Lisa (7–8), Suki (9–10) and Mark (11–12) – full details at 'http://cehs.montclair.edu/academic/iapc/docs/Curriculum_Brochure.pdf'. Each has an accompanying manual. Lipman's intention was that they be studied consecutively throughout schooling.

[22] See note 15 for some examples.

[23] However, there are a few articles discussing P4C and science education. See especially Lipman (1988) chapter 7 'Philosophy and Science Education at the Elementary School Level' (pp. 87–99) but also Clark (1994), Liao (1999), Novemsky (2003), Smith (1995), Weinstein (1990a, b, 1992) and the Ed.D. thesis of Ferreira (2004 – to be discussed below).

community of inquiry, she says, ‘students [will] … realize *for themselves* that science does not provide answers in the sense of closure … and that science itself is perhaps best conceived of as perpetual inquiry’ (p. 624, italics in original). This is not to say the CoI should supplant science instruction, but it should complement it (p. 629).

Despite this call, only a few people have gone on to develop materials in the science area. Often, the materials are one-off ideas for discussion starters, or local applications where the materials have not been made more widely available.[24] One of these was intensively researched for a doctoral dissertation (Ferreira 2004; see Ferreira 2012, for a summary).[25] Using chapter 1 of Lipman’s *Harry Stottlemeier’s Discovery* (1974) as a starting point, Ferreira wrote four additional chapters with a focus on classification, observation and inference in science. She then used the stories, accompanied by multisensory practical activities, in a semester-long Year 5 Brazilian science class, integrated into the school’s normal science (biology) programme. Using mainly qualitative methods, Ferreira showed that the use of these stories, within a community of inquiry, facilitated children’s learning of the target science process skills as well as other thinking skills, and encouraged reflection on those skills. Moreover, the students identified with the fictional characters, used them as models for their own thinking and also increased their abilities to self-correct and to build on the ideas of other students.

Below, I shall explore four programmes that have taken a more systematic approach to the use of a scientific community of inquiry (a fifth is explored in Hunt and Taylor’s article in this handbook). As we shall see, each of these approaches follows the Lipman classroom pattern of stimulus material, question gathering and discussion phase pretty closely, with the major variation between them being the nature of the stimulus.

48.3.4.1 Lipman’s *Kio & Gus*

The first is one of Lipman’s novels, *Kio & Gus* (1986), and its accompanying manual *Wondering at the World* (Lipman and Sharp 1986). To say this is a science programme is a little misleading, though there is a considerable emphasis on zoology and ecology, as the title of the manual implies. Aimed at children of around ages 7–8, the novel contains a wealth of philosophical and ethical hooks, as well as the scientific ones. In the preface to the manual, Lipman and Sharp

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[24] For example, the UK-based website p4c.com, which contains a resource area onto which teachers can upload materials they have developed, contains 20 one-off P4C science lessons. Web searches unveil references to other uses of the CoI in science education, e.g. Ling (2007), Cunningham (2011) and Phillipson and Poad (2010), but I have not been able to see the classroom materials used, beyond the description in the papers cited.

[25] Ferreira, now at the Universidade de Brasília, Brasília, Brazil, is overseeing several projects developing further P4C-based science education materials and researching their contributions to science education.

state that 'it is designed to be a complement to these sciences, rather than a substitute for them' (p. 1).

They canvass two ways in which the scientific community of inquiry can help: firstly, by providing 'logically disciplined, reasonable discussions' in which children can test their scientific hypotheses, models and concepts (at times, against the standard scientific ones). Just inviting them to 'exchange their myths for the truths offered them by science' is not enough: they must be 'allowed to think these matters through for themselves' (pp. 1–2). Special attention is paid to scientific concepts. They comment that 'scientific concepts, while generally definable by means of specific criteria and classificatory procedures, tend to appear to the early elementary student as inert rather than dynamic' (p. 3: one might extend this observation to much older students as well). However, scientific concepts need to be assimilated into the child's present understanding, and so 'exercises are provided to compel students to reason about the information essential to the concept under discussion' (p. 8).

Secondly, children need to 'think scientifically'. Their 'cognitive skills need to be cultivated … they cannot be cultivated in isolation from the discipline to which they must subsequently be applied … efforts to strengthen thinking skills in a 'content-free' manner are futile'. Scientific thinking should be addressed within science – it cannot 'be expected to develop naturally, and … be in place when needed' (p. 2).

Having said this, it must be noted that science only sporadically appears in the rest of the Lipman corpus. Lipman was aware of this (pers. comm.) and hoped that others would take up the job of writing such material. Moreover, the science in *Kio & Gus* is restricted to the life sciences, with no physics, chemistry or earth science. Lipman's approach requires dedicated time in the school timetable, as working through the novel *Kio & Gus* would take at least a lesson week for 1–2 years. While this is feasible in the early childhood years as an adjunct to science sessions, it would become less so in upper primary, and unlikely to be possible in secondary school.

48.3.4.2 Nevers and Colleagues' *Philosophizing with Children About Nature*

A long-running project in Germany has been concerned with the use of the community of inquiry in biology teaching.[26] In this case, the leaders of the project have had a dual aim: a pedagogical one of using the community of inquiry to deepen students' understanding of biology and its ethical implications while improving their scientific thinking and a research aim of understanding the ways in which children of different ages think about such matters, with a focus on issues of environmental ethics.

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[26] Gebhard et al. (1997, 2003), Nevers et al. (1997, 2006), Nevers (1999, 2005, 2009). Their work, in part, builds on the work of Helmut Schreier, who has been philosophising with primary school children about nature (among other issues) for many years (see, e.g. Schreier 1997; Schreier and Michalik 2008). None of his stories have, to my knowledge, been published in English.

The methodology used is similar to the Lipman approach outlined above. Purpose-written stories feature children involved in various different ethical dilemma situations characterised by a conflict of interest between a child or young person and a living organism or system. Hence, the major emphasis is on the interplay of biology and ethics. For research purposes, three sets of stories were used involving a plant, an animal or an ecosystem as the source of conflict, and each basic story was presented to different age groups (6–8, 10–12, 14–16). An example of such a story is in Gebhard et al. (2003, p. 95), and that paper, plus Nevers et al. (2006), provides copious transcripts of children's comments in discussion.

From recording, transcribing and analysing more than 150 group discussions, Nevers and her colleagues have been able to identify basic philosophical positions to which students subscribe, the nature and strength of the reasoning that they bring to bear on these positions, the consistency with which they hold them and their susceptibility to change in the light of discussions (Nevers et al. 1997, 2006).

A key finding is that children rely on anthropomorphism to moralise nature (Gebhard et al. 2003). This is effective when an animal or a tree is the source of conflict, but not with an ecosystem. In the latter case children tend to anthropomorphise individual organisms within the ecosystem and thus indirectly attribute moral status to it. Furthermore, the evidence indicates that anthropomorphism is not as apparent among older students. However, a follow-up study using a dilemma story involving trees and a questionnaire distributed randomly among university students suggests that anthropomorphic thinking is still prevalent among a large number of these students and drawn upon to moralise organisms, even if it is not expressed publicly.

In an individual case study, it was found that appealing to an aesthetically pleasing image from nature may serve to transform the discussion from unproductive circularity towards constructive compromise (Nevers 1999, p. 20; Nevers 2000).

Doctoral work by Hausberg (2012) under Nevers' supervision investigated the potential of philosophising with children for encouraging creative thinking (a sample of such work is to be found in Hausberg and Calvert 2009). The theoretical basis was a multifaceted model of creativity proposed by Urban (2004). Philosophical discussions with fifth and sixth graders were recorded and examined with a computer-supported text analysis system to identify various different categories of creative thinking and action. These included areas of cognitive thinking such as analysis and synthesis, analogy formation and metacognition as well as personal qualities such as humour and persistence. Group dynamic qualities such as the ability to elaborate and coordinate contributions from others were also identified.

A second phase attempted to assess whether the creative qualities expressed and trained by philosophising were applied in a different learning situation. Middle school students who had been philosophising in separate sessions for several years were presented with an open problem of biological nature and asked to discuss the problem in small groups, looking for possible solutions. Afterwards, the solutions were evaluated by the students in a moderated plenary discussion. Although it is not possible to conclusively demonstrate a transfer effect by these means, the evidence indicates that this is highly plausible. Almost all the forms of creative expression used when philosophising were also applied when the students dealt with an open biological problem, and solutions were proposed that went far beyond those usually found in biology classes.

48.3.4.3 University of Ulster's *Science in Society* Projects

At the University of Ulster, the *Science in Society* team has developed several packages based around the use of the community of inquiry, including:

- *Primary Community of Scientific Enquiry* (ages 7–11, for use in the subject The World Around Us, which includes science, geography and history)[27]
- *Forward Thinking* (ages 11–14, for use in science and/or citizenship)[28]
- *Community of Scientific Enquiry: Learning Science Through Dialogue* (ages 15–16, for use in GCSE Biology)[29]

While these resources are aimed at different age groups, all share a common structure: one or more starter activities; a trigger experience for students which consists of scientific information and/or experiments; a method for collecting the students' questions and deciding on the one to start discussing; an inquiry/discussion phase; and some sort of reflection on, or evaluation of, the inquiry. This is very similar to the Lipman model, except for the use of information sheets or experiments as the trigger for inquiry, instead of a story about similar-aged children discussing science.

As the overall title of the project implies, one of the emphases in the materials (particularly the *Forward Thinking* package) is on ethical implications and social impacts of science. Even with this package, though, the experience of the team is that students also want to explore philosophical questions about the nature of science and inquire into the science involved, including the meaning of scientific concepts (Dunlop 2012; Dunlop et al. 2011). The primary materials concentrate more on scientific content and processes – especially physics and chemistry – while the GCSE materials consciously target all these areas.

An integral part of the project involves evaluation of the impact of the scientific community of inquiry, though this is at an early stage. In the only peer-reviewed evaluation study published at the time of writing, Dunlop et al. (2011) present evidence that lower secondary students taking the programme enjoy their science more, engage with each other more, deepen their understanding of the science covered and correct and question each other more. Teachers agreed that better learning takes place and the quality of scientific reasoning improves and found that they had clearer access to student misconceptions. Several commented that the discussions worked best when the students had already been exposed to factual background

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[27] See http://www.ulster.ac.uk/scienceinsociety/pcose.html, where you may read the teacher support material and student handouts, and also Dunlop et al. (2011).

[28] See http://www.ulster.ac.uk/scienceinsociety/forwardthinking.html, also Dunlop (2012).

[29] Still in development

information, suggesting that the best time for a community of scientific inquiry may be after prior learning or research.

The materials are, at present, used by teachers involved in the project, who have engaged in training in their use and often have the in-class support of the researchers. The potential to publish the materials more widely exists, but it seems to me that they would require considerably more support material before teachers could use them effectively, independently. Such an outcome is desirable but may depend on continued funding.

48.3.4.4 Sprod's *Discussions in Science*

Finally, I have developed a suite of 18 connected short stories,[30] with teacher support material, for use in middle schooling (roughly, ages 10–14) (Sprod 2011). These include material from physics, chemistry, biology and the earth sciences and are designed to be used within a science programme, as they contain links to related experiments and theory. Their use follows the standard Lipman pattern of reading the story around the class, gathering the students' questions and entering a discussion based around the question chosen by the class. The teacher support material includes information about the scientific, philosophical, ethical and social issues that lie behind the stories, discussion guides (lists of questions that teachers may draw upon to unpack the issues) and suggestions for related activities, such as experiments or research projects.

Underpinning this approach, and in particular a number of the stories, are several research studies in which I participated. The first stories were written for an investigation of the impact of the scientific community of inquiry on students' ability to reason scientifically, which demonstrated statistically significant gains for the experimental group over a control group in a pretest/posttest design (effect size: 0.70) (Sprod 1998). Discourse analysis of the use of epistemic episodes (Sprod 1997a) in the discussion provided support for the interpretation that the improvements were due to the internalisation of improved group thinking in the class discussions. Both these papers contain transcripts of discussion excerpts from the experimental Year 7 (lower secondary) class.

The content of three of the stories in the collection are based on an investigation of how children come to understand the way light and vision are coordinated.[31] Characters in the stories represent different conceptions of the nature of light and how objects and the eye interact with light. Further stories likewise draw on a wide range of children's misconceptions, scientific theories, philosophical accounts, ethical controversies on scientific applications and my own experience of teaching science over many years.

The stories are linked through the narrative device of a group of children discussing their experiences of science and the world, trying to make sense of it. Thus, the

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[30] These stories can be read at www.acer.edu.au/discussions-in-science/.

[31] Collis et al. (1998), Jones et al. (1997), Sprod (1997b), and Sprod and Jones (1997).

stories make use of the power of narrative, though they are different in conception from stories drawn from the history of science as discussed by Klassen and Klassen elsewhere in this handbook. Matters that are embedded in the stories include the teasing out of the meaning of scientific concepts, puzzles about scientific methodologies and the nature of science, ethical concerns about the practice and applications of science, and issues about the links between the science students are learning and their everyday lives. Throughout, both through the encouragement and modelling of rigorous thinking in the discussions and through explicit consideration, the skills and dispositions of scientific thinking are addressed.

In this list, we can see that the community of inquiry holds great promise for dealing with many of the concerns that form the subjects of chapters in this handbook. Further, by harnessing the power of narrative and drawing on the method of allowing the students to set the agenda from what they find interesting in the story, they can do so in a way that lends them ecological validity – they fit into students' expressed interests and connect to their lived experience. To pick only a handful of examples, I can instance conceptual puzzles such as those about energy (Bevilacqua), light (Galili) or ecology (Korfiatis, Lefkaditou & Hovardas); considerations of the methods and nature of science such as controversies in earth science (Dolphin & Dodick), understanding the purpose of practical work (Ford) or getting a feel for scientific inquiry (Kelly); inquiry into ethical issues (Cuoló); exploration of scientific modes of thinking such as the use of models (Kopenen & Tala), thought experiments (Asikainen & Hirvonen), coordination of the macro and micro levels (Guisasola) and the nature of scientific argumentation (Bravo); and finally links to the everyday through developing scientific literacy (Norris, Phillips & Burns) or considering multicultural issues in science (Horsthemke). All of these are raised at some level in one or other of my stories, for possible consideration in the scientific community of inquiry.

48.4 Summary

48.4.1 Survey of Conclusions

This chapter has surveyed briefly some of the research into the improvement of thinking through education and whether and how it might be taught, particularly in the context of science education.

As we have seen, the preponderance of the evidence is that thinking is complex – having at least critical, creative and emotional (caring) aspects – and always takes place within a context. Nevertheless, there is a core of general thinking that can be learned and used within one context and then, provided the conditions are right, transferred to other contexts. Moreover, considerable evidence indicates that we can improve children's thinking by developing their capacities and dispositions for higher-order thinking and strengthening their judgement. Whether we are right in claiming that we are accelerating development that would otherwise take place somewhat more slowly or that we are equipping them in ways that they may not otherwise achieve is not yet entirely clear.

The evidence also supports the view that good general thinking is supplemented by more specialised thinking capacities within different domains, though it seems these capabilities probably develop from more general ones. We might draw the conclusion from this that any general thinking skills programmes ought to be supplemented by attention to improving thinking within each discipline and hence in all subjects in schools. Alternatively, we might conclude that if each subject strives to improve thinking within its own domain, then there will be no need for a general thinking skills programme. Either way, there is a strong argument for including an explicit element designed to improve thinking in science courses at all levels of education. A meta-analysis of critical thinking courses (Abrami et al. 2008) bears this out in its finding that the most effective critical thinking courses combined an explicit focus on thinking capacities and dispositions with application to a particular content area.[32]

Concentrating further on thinking within the domain of science, we have seen that scientific thinking seems to draw on both the general thinking capacities and dispositions that apply across all domains and more specialised scientific thought processes (which are, in any case, not identical in all scientific categories). Just what the categories and attributes of such advanced scientific thinking are does not seem to have been researched in sufficient detail. Moreover, there has been little work done on exactly how young children – who in their science lessons are presumably utilising generic thinking – develop through their education (primary, secondary and tertiary) the more specialised scientific thinking required by professional scientists or, more importantly for most, scientifically literate citizens.

Nevertheless, we do have a good deal of evidence that the teaching of scientific thinking is not done particularly well in schools at present. In large degree, this seems to be because the improvement of scientific thinking needs to have an explicit focus in science lessons, while generally it does not. While there are copious case studies in the literature of individual teachers whose teaching style does encourage better thinking by making it explicitly visible to students, such approaches have not been widely implemented at a system level.

However, we have seen that there are good models, supported by robust research, for such an approach, and have looked in some detail at two: the Cognitive Acceleration through Science Education and the Philosophy for Children programmes. It seems clear that both programmes (together with the Conceptual Challenge in Primary Science project) share some important and powerful features. They 'begin in wonder' (puzzlement, cognitive conflict), as Aristotle (1998, 982b12) put it in Book 1 of the Metaphysics; use rigorous dialogue (social construction); turn attention explicitly on the thinking taking place (metacognition); and address transfer or bridging, all in the context of science. In other words, such programmes make both student and teacher thinking – and the quality of that thinking – the

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[32] They also found that including explicit thinking outcomes in the aims of the course and providing professional development for teachers in the improvement of critical thinking were important factors.

subject of an inquiry visible to all: it is ‘minds-on’ science. The obvious conclusion is that other science programmes, provided they incorporate similar features, are likely to be similarly effective.

48.4.2 A Challenge to These Conclusions

Reconsidering his 2004 paper that largely agrees with the conclusions above, Davson-Galle (2008a, b) has called into question, firstly, whether it is legitimate to teach the nature of science and critical thinking within science at school and, secondly, even whether we can justify compulsory science courses at all. There are two major grounds for these challenges. The less radical is based on a cost-benefit analysis: would the time allocated to such aims be better spent in teaching something else – say, more science content? More controversially, he questions the legitimacy of overriding students’ autonomy in compelling them to study science. As he acknowledges, this latter challenge can be applied to much, if not all, of education.

Turning to the first challenge, I believe that Davson-Galle has created a false dichotomy: either we teach scientific thinking and the nature of science or we teach science content. Doing one can only be at the expense of the other. Consideration of the research cited above – particularly the longitudinal studies in CASE – seems to show that sacrificing curriculum time to the improvement of scientific thinking does not result in students learning less scientific content, at least as measured by outcomes in later science external exams. Rather, it makes the learning of science content faster and more effective. The evidence for learning about the nature of science is less clear cut, as it has not been as explicitly tested, but if that learning is merged with the improvement of scientific thinking, through a dialogical pedagogy, there are reasons for thinking that similar claims are justified. However, there is probably a need to test this hypothesis more directly.

Davson-Galle’s second challenge is somewhat beyond the scope of this review. However, I believe that it is based on a misconception of the notion of autonomy, which assumes that it is a characteristic that students just have. In my view, autonomy is rather a capacity which students develop, particularly through improving their ability to think well – see my analysis of communicative autonomy in Sprod (2001, especially Sects. 2.4, 2.5, and 3.2). Our justification for compulsory education is then that it is an effective way to build autonomy and that the more an educational programme contributes to such building, the more justified it is.

48.4.3 Further Work

Given that such programmes are not as widely included in science courses as perhaps they ought to be, I will finish by considering what further work is needed. It seems to fall into three categories.

Firstly, the research foundation for improving the teaching of scientific thinking could be considerably stronger. Both CASE and P4C (though, for the latter, not in the context of science education) have research to indicate that long-term, far transfer of the improvement of thinking takes place. However, these studies have not been fine grained enough to explore the relative impact of the various factors I have mentioned above, let alone variations that arise from differences in the way they are implemented or the cultural context in which they are applied.[33] Adey et al. (2007) are surely right to call for more research that uses large-scale longitudinal studies, well designed to tease out such factors, across a variety of social settings. We need to refine our understanding of the conditions that are truly effective in developing scientific thinking in all its aspects, and we need to study whether the various programmes have other desirable effects, such as strengthening learning communities, enhancing enjoyment of science, improving ethical judgement in matters scientific, illustrating the nature of science and deepening conceptual understanding.

Moreover, we can question how we ought to interpret ‘long-term, far transfer’. Certainly, both the CASE and the Tricky and Topping P4C research show measurable effects several years after intervention finishes. But is this long term enough? Surely we would want to see effects that last well into adulthood, and the research to show this has not been done (indeed, such research faces considerable practical difficulties). Additionally, the CASE studies did not test the long-term maintenance of improvements in thinking directly. Rather, results of external exams or testing were used as a proxy. We are only surmising that the experimental students still think significantly better than their control peers.

Of course, showing effects on more general tests does strengthen the claim for far transfer, especially when the CASE work shows effects outside the science domain. But we can question whether the effects extend even further: into thinking in everyday life, or in making citizenship decisions, to choose two examples.[34] Such claims are often made, but research backing for them is lacking. While it is desirable to improve students’ exam results and to foster more and better research scientists, for a far greater proportion of students, the justification for seeking to improve scientific thinking rests rather on creating thoughtful and scientifically literate citizens. We ought to be gathering evidence to allow us to ascertain whether such outcomes occur.

Secondly, one of the factors not addressed in much of the research done so far is the impact on the success of such programmes of the background, attitude and competence of the teachers who deliver the programme. Much of the research surveyed in this chapter investigated the impact of the researcher’s own teaching on thinking (especially in the small-scale studies) or that of teachers who had volunteered to

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[33] Indeed, we should note that, as correlational studies, such research does not show conclusively that improving students’ scientific thinking through dialogue causes better science learning and hence exam results. It is possible that some other factor – such as an improved attitude to science – is at play.

[34] Note that this possibility depends on such programmes encouraging generalisation of thinking abilities across contexts – a matter discussed in Sect. 48.2.1 above.

take part, often because they were already experienced in the programme being studied or because they had a long-standing sympathy for such approaches. Clearly, such studies are open to experimenter effects. If such programmes are to be widely implemented, then teachers from all sorts of backgrounds, with a variety of prior training and quite diverse attitudes towards what constitutes good science teaching, are going to be involved. Only large-scale studies that recruit all (or a random sample of) the teachers in the study population to implement the programme are going to be able to tell us about the impacts of such teacher attributes on the success of the programmes. Indeed, the research design of such studies will need to ensure the right data are collected to give us better knowledge of teacher effects.

Such considerations bring us to the third reflection. Successful implementation of effective ways of improving scientific thinking will depend on having capable, well-trained teachers delivering them. Research repeatedly shows that teachers are the most important in-school factor in student achievement: the ‘evidence supports the assertion that the effects of teachers far exceed the independent effects of schools’ (Manzano 2000, p. 60).

Yet Adey and his colleagues comment that teaching in a way that improves students’ scientific thinking:

> is difficult to do. Teaching for cognitive stimulation is far more demanding, and seems far more risky in the classroom than is efficient instruction in content matter. Amongst others, Adey et al. (2004) have described the extent of the conceptual-pedagogical change that teachers must make to move from one form of teaching to another. (Adey et al. 2007, p. 93)

Given this, the training provided to teachers needs to be effective in helping them to make permanent modifications and additions to their practice, whether it is delivered during initial teacher training or to teachers already working in schools. Such effective professional development, of course, requires capable providers and can be resource hungry. Again, research into the efficacy of professional development and the factors that make it more effective could assist us to improve such provision.

Finally, there is a need to develop more materials to support teachers in this modified approach to science education. While the CASE materials do provide a coherent set of activities for the first 2 years of secondary school, as well as the *Let’s Think Through Science* books for 7/8-year-olds and 9/10-year-olds,[35] these activities address only parts of the science that students could be learning and are tied to the English National Curriculum. Moreover, they tend to target particular scientific thinking capabilities, rather than content areas. In the P4C field, the materials available are even less systematic. Thus, teachers looking for an activity to engage in ‘minds-on’ science that specifically fits into a unit they are developing are unlikely to be able to find one. Science teaching has multiple aims, among them ones like covering content and developing practical skills, which are probably not best approached through the discussion-based activities considered in this chapter. A teacher who is trying to put together a unit of work in science that covers all these

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[35] See http://www.cognitiveacceleration.co.uk/resources/other_subject_resources.html.

aims will be looking for an activity that fits in neatly: at present, the choice is limited. Moreover, there is not an even coverage over all the subdisciplines of science, with perhaps an overemphasis on the life sciences.

In summary, then, this chapter makes the case that it is possible, by making the right sorts of additions to the pedagogical toolboxes of teachers, to deliver science education courses in a way that strengthens students' scientific thinking, as well as other desirable outcomes: a deeper understanding of the concepts of science, the nature of the scientific endeavour, the ethical implications of science and greater links between the science learned and the students' everyday lives – arguably, without sacrificing student mastery of scientific content and skills. At the core of the successful methods lies discussion that is recognisably philosophical.

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Chapter 49
Informal and Non-formal Education: History of Science in Museums

Anastasia Filippoupoliti and Dimitris Koliopoulos

> *I, Clio the Renowned, eldest daughter of Mnemosyne, Muse of History, warden of memory, wish to teach men lest they neglect the past of their knowledge as of their ignorance.*
>
> (Jean Marc Levy-Léblond 2012)

49.1 Introduction

History of science has a long presence in formal science education. During the late 1960s and early 1970s, an educational movement emerged (mainly in the Anglo-Saxon literature) that argued for the benefits of using the history of science in secondary education. Initial references also carry some preliminary perspectives on the advantages and disadvantages of such a partnership (Brush 1969, 1974; Klopfer and Cooley 1963). These perspectives characterise the research field diachronically, but the issues of instructional strategy choices and methodological techniques with which history of science can be effectively linked to science education are still open research questions.

The use of history of science in formal education is related to three trends in educational research:

1. A humanistic approach to science teaching that aims to contribute to the 'broad cultivation' and scientific literacy of pupils as citizens (e.g. Klopfer 1969; Langevin 1964; Matthews 1994/2014)

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2. The development of student understanding of the nature and characteristics of scientific knowledge, mainly via the 'nature of science' educational movement (e.g. Hodson 2008; Lederman 2007)
3. The cognitive development of pupils and the shift of interest from methodological to conceptual dimensions of scientific knowledge (e.g. Monk and Osborne 1997; Nersessian 1992; Strauss 1988)

Despite the increasing influence of the history of science in formal science education during recent decades, one cannot ignore the difficulties and the obstacles that a broader educational use of the history of science faces. Among these, Hottecke and Silva (2010) refer to the negative stance of educators to any proposed change to the traditional teaching culture and the boundaries imposed upon educators by the official science curriculum that either ignores or degrades the role and importance of history of science in teaching.

It is interesting therefore to examine what happens with the kind of dissemination of history of science that originates or relates closely to the modern science museum. The dissemination of history of science is related in this case with informal and non-formal educational approaches.[1] What are the aims of this sort of dissemination, how are they achieved and how are they related to non-formal and informal education? The present review aims to bring forward these issues and open a potential academic discussion. We first discuss the types of museums that have been developed; we then analyse the history of science as an exhibition and communication element; and finally, we approach the subject as an educational element. The review will not address how the science museum is being treated as a research subject itself by historians of science.

49.2 A Definition of a Science Museum and the Types of Science Museums

Museum studies have grown since the late 1960s following a considerable rise in the number and types of museums worldwide. Museum studies literature offers a wealth of definitions and classifications of museums organised mainly according to

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[1] In the present article, the terms *informal education* and *non-formal education* are considered as distinct terms (Coombs and Ahmed 1973; Escot 1999; Eshach 2006). An *informal* educational process is not an organised and systematic one that occurs in different educational settings (schools, museums etc.). It is a process – quite often unintentional – offered by the personal environment of an individual. The interrelationship between the individual and the exhibition during a museum visit is a typical example of an informal educational process. In contrast, *non-formal* educational environments are related to autonomous cultural institutions that provide scientific knowledge, such as museums, and are environments that offer organised educational activities (as in the case of educational programmes in museums or programmes that are organised between school and museum).

the academic disciplines to which they refer through their collections, exhibitions and public programmes.

The science museum is not a homogenous entity. The nature and characteristics of the science museum can be studied through the variety of categorisations produced by both museum professionals and museum researchers. These categorisations group museums based either on the way in which these institutions confront collecting, displaying and interpretation of objects and the way they conceive exhibition space (Wagensberg 2004) or on the evolution of the science museum (de Clercq 2003; Friedman 2010). The latter are significant not solely because the history of the museum as social institution as demonstrated by the related literature on the history of museums and collections is a vital subject (Arnold 2006; Findlen 1989, 1994; Impey and MacGregor [1985] 2001; Yanni 1999), but also because this literature can be used to interpret the function of modern science museums by either researchers coming from fields of inquiry other than museum studies (i.e. science educators) or by science teachers (Koliopoulos 2003).

A history of the science museum goes back to the Renaissance collections of curiosities and learned cabinets (e.g. the cabinet of Francesco I de Medici in Florence (Findlen 2000; Pearce 1993) and the collections of seventeenth-century philosophical and scientific institutions (e.g. collections held by the Royal Society of London). During the second half of eighteenth century, along with the founding of the first public museums, a number of museums of natural history were established. Unlike the earlier cabinets, these were public institutions allowing a large number of visitors into their exhibition spaces. In addition, the galleries exhibited objects according to a classification system that was closely adapted to distinct academic disciplines.

These institutions praised the collected object (e.g. scientific instruments, natural history specimens and technological artefacts), accumulated natural curiosities and man-made artefacts and favoured the wooden or glass-case presentation. The *Musée des Arts et Métiers* in Paris is an exemplary case reflecting this exhibition philosophy (Ferriot and Jacomy 2000). There the visitor was considered a passive admirer of a glorious scientific past. The act of interpretation was not facilitated by the museum curator, although some interpretation was provided by a few means such as the object's label. In this context, scientific objects were displayed as art objects and admired by the upper class (Bennett 1995). The *Natural History Museum* in London took a similar approach.

University science collections fall into the same category given that most of them have been created to act as repositories of worn and outdated scientific apparatus once used in the teaching of physics and chemistry or collections of objects related to the natural sciences (e.g. stuffed animals). The museum of the King's College London that was founded to host the King George III science collections in mid-nineteenth-century London is an interesting case in point, yet by the end of the century it had become a mere repository (Filippoupoliti 2011).

Between the middle of the nineteenth century and World War II, another type of museum emerged that differed from the traditional museums just described. During this time, museums also embraced an explicit educational mission following the mid-nineteenth-century demand for educating the lay public. Interpretation of the exhibition was performed by presentation of a series of objects that reflected a certain scientific concept or idea, and an attempt was made to form concise units according to certain scientific themes (e.g. energy, power, physics etc.). The *Science Museum* in London (est. 1885) and the *Deutsches Museum* (est. 1903) in Munich are examples of this category, although in recent decades these museums have enhanced the exhibition space with modern design and interactive exhibits. Along with the older galleries, a series of interactive hands-on exhibits are presented to update the established scientific narrative (Durant 2000). This category also includes the *Museum of the History of Science* at Oxford (est. 1925) and the *Whipple Museum of the History of Science* at Cambridge (est. 1944), the former *Istituto e Museo di Storia della Scienza* now the *Museo Galileo* (est. 1927) in Florence and the *Museum Boerhaave* (est. 1928) in Leiden, Holland (de Clercq 2003).

Although science centres differ from science museums, they are usually treated together in the literature. A science centre has a distinct experimental philosophy that moves from the display of the authentic object to create an original/meaningful museum experience through active visitor participation. Beyond object worship, it is the exhibition space that matters more as it assimilates the laboratory, a gallery of research and a place of demonstration. Historically, this type of a science institution can be traced back to the 1930s, when the *Palais de la Découverte* in Paris was founded according to a rationale relevant to the division of academic scientific disciplines, followed by the San Francisco *Exploratorium: The Museum of Science, Art and Human Perception (*est. 1960s), which is regarded as the 'father' of science centres (Hein 1990; Cole 2009). Another example is the *Cité des Sciences et de l'Industrie* in Paris, in which the focus of exhibition activity is the social use of natural sciences and technology (Caro 1997; Zana 2005). This science centre has created a special children's science museum that offers exhibitions and activities designed to address the cognitive and emotional needs of young children (Guichard 1998).

The development of science centres has considerably influenced museological approach and museographical practice of even the most traditional museums. For example, the recently renovated *Museo Galileo* in Florence and the *Museum of the History of Science* at the University of Oxford have improved their approaches to the display of objects. They have modernised the permanent and temporary exhibitions as well as their communications approach to the public (e.g. including new interactive activities as part of an exhibition and providing virtual tours via the museum website). The hybrid form that such museums have become raises the issue of establishing a new educational identity for these institutions (Quin 1993).

We pose the following questions which we will tackle in the following section: How does each of the science museum types implement the history of science in exhibition and educational practice? What sort of interpretation do they offer? Do each of these different interpretation patterns offer the same epistemological status and give a certain communication role to the history of science? Does the history of science constitute one of the seminal elements in the diffusion of scientific knowledge communicated via science museums, or are museums designated solely for the history of science the only appropriate institutions to research, exhibit and diffuse objects, ideas and issues related to the history of science?

49.3 History of Science as an Exhibit and Communication Element

History of science is an exhibited theme found in a variety of museum types. Museums of the history of science distinctly safeguard, interpret and display the material culture of science (Bennett 1997, 2005; Camerota 2011). Museums of the history of science are usually university museums that base their foundation on collections of scientific instruments and apparatuses once used in research and university teaching or on private collections that have been donated to the museum. Two characteristic examples are the *Museum of the History of Science* in Oxford (established 1924) by the gift of the collection of Lewis Evans[2] to the University and the *Whipple Museum of the History of Science* at the University of Cambridge founded in 1956 to house Robert Whipple's[3] collection of scientific instruments and rare books (Bennett 1997; Taub and Willmoth 2006). In these institutions, the history of science is present in many ways, most importantly in the use of elements of the history of science in exhibitions in which a part or the majority of the scientific collections (authentic scientific instruments or biological specimens) are used.

How then does a museum of the history of science differ from a science museum? Bennett (2005) notes that

> museums of the history of science contain old instruments and apparatuses, just like any science museum … If it is not the nature of the collections that is different, it should be the assumptions about what the collections are for, which will inform how they are selected and how they are used. (pp. 606–607)

Because of their privileged relationship with academic history of science, museums of the history of science can certainly provide exhibitions of their collections that gain their meaning from the cognitive, methodological and cultural dimension of the history of science.

Another category of science museum where history of science is present includes those institutions whose historical tradition, collections and particular museological/museographical approaches make possible the presentation of a history of science exhibition narrative even though the history of science is not a distinct part of the institutional mission such as university museums that hold collections of scientific instruments and natural history and biological specimens (Tucci 2002; Lourenço 2005; Subiran et al. 2009). One difficulty that this type of museum confronts in presenting collections to the broader audience is the absence of a unified and coherent theme

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[2] Lewis Evans (1853–1930) was a collector, brother of the notable archaeologist, Sir Arthur Evans, who excavated the Palace of Knossos, Crete (Greece). See also P. de Clercq, Lewis Evans and the White City Exhibitions, *Sphaere. The online journal of the Museum of the History of Science, University of Oxford,* available at http://www.mhs.ox.ac.uk/sphaera/index.htm?issue11/articl4.

[3] Robert Stewart Whipple (1871–1953) donated more than 1,000 scientific instruments to the University of Cambridge in 1944. See also S. De Renzi (1998). Between the market and the academy: Robert S. Whipple (1872–1953) as a collector of science books. In R. Myers and M. Harris (eds), *Medicine, Mortality and the Book Trad*e (pp. 87–108). St. Paul's Bibliographies: Oak Knoll Press.

topic that could become the basis of an institution recognisable by non-experts (Antoine 2010, p. 9). One such theme topic, according to Antoine (2010), is the implementation of the scientific method via elements from the history and philosophy of science.

Non-university museums such as the *Musée des Arts et Métiers* in Paris and the *Science Museum* in London that hold scientific collections are good examples of this category of museum. Although their original aim was not the dissemination of the history of science,[4] today these museums are ideal places for the display of science because of the richness of their collections. Also, institutions such as centres of scientific research and for the popularisation of science (e.g. *Royal Institution of Great Britain*), scientific institutions (e.g. *Royal Observatory*, Greenwich, England) and laboratories or the private premises of eminent men of science that have become house museums (e.g. the *Charles Darwin Down House* in England and the *Maison d'Ampère* in France) are potential places for disseminating the history of science.

The implementation of history of science can differ among museums according to their type. Studying three institutions that display collections of historic astronomical instruments, Maison (2002) suggested three different ways of exhibiting such collections. The *Musée des Arts et Métiers* emphasises the technological dimension of the displayed scientific instruments, and the exhibition is based on historical evidence that presents a holistic view of the technical culture from Renaissance to the present day. In contrast, the *Observatoire de Paris* emphasises the concepts of the physical sciences and how these are intertwined with the function of astronomical instruments. Finally, the *Royal Observatory of Greenwich* displays collections with the aim of presenting the social and economic aspects related to the development of astronomy research over time.

Finally, even though science centres don't hold any permanent collections of authentic/historical objects, occasionally they may host temporary exhibitions that present elements of the history of science. These centres seem to function as contemporary scientific textbooks that, according to Kuhn, can hide the process of how scientific knowledge is obtained. If someone replaces the word 'textbooks' with 'science centres' in the next extract, the meaning would not be twisted:

> Textbooks thus begin by truncating the scientist's sense of his discipline's history and then proceed to supply a substitute for what they have eliminated. Characteristically, textbooks of science contain just a bit of history, either in an introductory chapter or, more often, in scattered references to the great heroes of an earlier age. From such references both students and professionals come to feel like participants in a long-standing historical tradition. Yet the textbook-derived tradition in which scientists come to sense their participation is one that, in fact, never existed. For reasons that are both obvious and highly functional, science textbooks (and too many of the older histories of science) refer only to that part of the work of past scientists that can easily be viewed as contributions to the statement and solution of the texts' paradigm problems. Partly by selection and partly by distortion, the scientists of earlier ages are implicitly represented as having worked upon the same set of fixed problems and in accordance with the same set of fixed canons that the most recent revolution in scientific theory and method has made them seem scientific. (Kuhn 1970, pp. 137–38)

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[4] Moreover, history of science as an academic discipline emerged later.

What is the mode of history of science as an *exhibition narrative*? Which one of the history of science narratives one occasionally confronts in museum exhibitions? Are historical facts explained and interpreted? Is emphasis being given to historical moments/turning points and the importance of controversies and scientific revolutions? Is it more important to research science as a social action that is formed by the social-historical-cultural context? Or is it more seminal to trace the history of science as a history of ideas or as an exploration of the material culture and non-literary traditions? A first attempt to answer these questions will be presented in the following paragraphs.

Even though history of science as an academic discipline emerged during the first part of the twentieth century, historic scientific instruments were already on display by the second half of the nineteenth century in museums such as the King's College London King George III Museum as well as in international/world exhibitions such as the Special Loan Exhibition in London in 1876. Historian Steven Conn has called the museum exhibition culture of that period an 'object-based epistemology' (Conn 2000). According to that perspective, the exhibited object (e.g. a scientific instrument) is able to confirm and support the 'scientific power' of a phenomenon or an idea and therefore as a historic object can stand as a symbol of scientific progress. For many decades in the early twentieth century, museums preserved the type of museological narrative that they inherited from their nineteenth-century predecessors. For instance, scientific instruments and apparatuses were preferably displayed in a thematic way, and their mode of display reflected an encyclopaedia of natural sciences in which each displayed object stood for a particular scientific phenomenon or process.

During the 1980s, shifts in the museological and museographical approach to science museums (Schiele and Koster 1998) in research trends in the history of science and in the increasing interest of historians of science in science collections led to important changes in the ways museum curators displayed the history of science in exhibitions. At least three epistemological approaches can be identified in these museum exhibitions. The first approach is the traditional one mentioned earlier that treats the history of science as the documentation of objects and facts. The second approach treats the history of science as a history of ideas and is not broadly used to weave a narrative into a science exhibition. In this case, the authenticity of the science collection is of minor importance (i.e. whether objects are historic scientific instruments or reconstructions). Emphasis is being given to how an idea (or ideas) is born, developed and cognitively treated in order to give meaning to objects. The *Grande Galerie de l'Evolution* of the *Muséum National d'Histoire Naturelle* in Paris focuses on the evolution of species (Van Praet 1995). Other examples of such an exhibition approach include the following: The exhibition 'Exploring the World, Constructing Worlds: Experimental Cultures of Physics from the sixteenth to nineteenth Century' in the *Museum of Natural History and Pre-History* in Oldenburg, Germany (Heering and Muller 2002), which addresses issues such as 'astronomical and experimental practice in the sixteenth and seventeenth centuries' and 'the science of precision measurement in the nineteenth century' and the Galilean exhibit of the *Exploratorium* in San Francisco, entitled ‘The Gravity-Powered Calculator’, which was also reconstructed by Cerretta (2012).

Exhibitions belonging to the above-mentioned two categories aim at disseminating the content, the process and the product of science from an internal point of view, the view of science. In contrast, a third approach considers trends in the history of science literature that view science as an example of culture with particular practices and tools that are affected, developed and transformed according to the cultural and historical context in which they have been developed, including non-scientific factors (Golinski 1998; Galison and Thompson 1999; Daston 2000).

In addition, the emergence of Social Studies of Science since the 1980s has provided researchers with fresh perspectives on understanding the intersection of scientific practice and culture (Latour and Wooglar 1986; Latour 1987). In this context, emphasis is given to how scientific practice is being formulated in the laboratory and in the performance of crucial experiments (Arnold 1996; Chittenden et al. 2004). For instance, the exhibitions hosted at the *Wellcome Collection* of the Wellcome Trust in London and the temporary exhibitions hosted in the Science Museum in London and the Nobel Museum in Stockholm are examples of cultural turns in the reading of the history of science.[5] From the perspective of science education, Pedretti (2002) also refers to the use of the history of science by science museums addressing socioscientific issues.

The above-mentioned modes of introducing the history of science in museums lead to informal education and informal learning. Museum visitors and school groups in particular can gain an interest in science as well as gain a popularised conception of the content and method of science (Stocklmayer et al. 2010). However, this kind of popularisation eliminates the systemic dimension of the meaning of scientific and historic knowledge and consequently sometimes deforms and transforms it to such an extent as to alter totally its meaning and, in still other instances, leads to paradoxical assertions (Jacobi 1999; Jurdant 2009). The risks stemming from the popularisation of scientific and historical knowledge could possibly be reduced if museums place more emphasis on the educational dimension of communication and on their function as institutions for non-formal education (Escot 1999). This issue will be analytically treated in the following section.

49.4 History of Science as an Educational Tool

Science museums are gradually increasing their emphasis on their science education functions (Teichmann 1981; Tran 2007; Stocklmayer et al. 2010). Museums produce a wealth of educational material for all types of visitors, the design of which varies according to type, content and creator. For instance, some materials are composed by

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[5] See, for example, the Nobel Museum Centennial exhibition *Cultures of Creativity* (Stockholm, Sweden) which examines creativity in science. Available at http://www.nobelmuseum.se/en/exhibitions/cultures-of-creativity

in-house museum professionals linking the programme directly to certain exhibits and perhaps implying that an exhibit can easily be transformed to educational material.

Many science museums design programmes in collaboration with schools and other educational institutions, either because they seek to consider the concerns raised by such institutions or because they seek theoretical and/or practical tools to support exhibit design. University departments that offer postgraduate museum studies courses or science education courses provide essential support towards the design of meaningful educational programmes for museums' visitors. Does the history of science have a specific role in the design of museum educational programmes? Do science museum professionals need formal education about how to give certain meanings to science collections through the aid of history of science, exhibitions and associated narratives? Or, is non-formal/informal education sufficient to act as a means of diffusing scientific knowledge?

Our review of the educational tools used by museums to communicate the history of science elements identified four categories of educational material:

(1) *Guided tours focused on narratives from the history of science.* This is the simplest educational intervention, engaging the history of science in a sequential science museum-guided tour. These tours typically present stories of people, ideas and/or practices from the history of science field and may contribute to raising the interest of visitors for the exhibition or to making meaning from an exhibition.

    For instance, Fadel (2011) uses history of science elements in lectures given during the performance of experiments at the *Palais de la Découverte* in Paris. He notes that the history of science can be a very powerful tool for introducing a new concept, idea or theory. Sometimes, stories and anecdotes taken from history are helpful as brief breaks to keep the attention of the audience. In other cases history can help people realise how answers to questions always seem obvious when one already knows the answer but seldom are apparent beforehand (Fadel 2011).

    In formal education, the design and narration of stories that introduce elements of the history of science is a common practice (Stinner et al. 2003). Unlike formal education, during a guided tour in the museum, the guide cannot expand the narration to explain a topic in detail. In this context, guided museum tours using narratives from the history of science are the weakest type of educational programme for presenting the history of science.

(2) *Museum educational programmes/workshops.* These activities are designed mostly for students and teachers, not the general public. In many instances, these programmes are developed and performed by specialised museum educators (Tran 2007). The *Deutsches Museum* is one example of a successful implementation of history of science elements in museum educational programmes. Teichmann (1981) points out that

    > historical objects displayed are to be integrated into the other educational activities of the museum and not simply remain commemorative pieces; i.e. historical collections and modern didactics are to be united according to the following aspects: (a) often modern situations can be clarified by means of historical explanations; (b) the completely different conditions of the past and the then existing specific difficulties in the realization of new

> knowledge, can offer a valuable lesson in questioning the apparently foregone conclusions of today; (c) the incorporation of modern and historical objects into the framework of human science and cultural development, can exhibit the characteristic position of science and technology (p. 474).

Educational programmes are structured educational environments designed to acquaint students and teachers with scientific and historical knowledge in a systematic way. For example, the context for knowledge could be the experimental history of physical sciences (Sibum 2000), the construction of concepts and methods via the reconstruction of artefacts or historical experiments (Teichmann 1999; Heering and Muller 2002) or the historical development of our understanding of the taxonomy of biological organisms (Faria et al. 2012).

(3) *The collaboration between museums and formal education.* Many researchers have argued that the collaboration between school and museum can promote achieving both cognitive and emotional student outcomes. A number of studies suggest that the museum visit and the children's activities during the visit should be accompanied by school before and after the visit (Griffin and Symington 1997; Anderson and Lucas 1997; Anderson et al. 2000; Guisasola et al. 2005; Guisasola et al. 2009). Other researchers claim that the involvement of teachers in non-formal educational settings such as science museums should be part of teacher training in science and pedagogy (DeWitt and Osborne 2007).

Unfortunately, studies of the development and evaluation of educational programmes in museums that introduce elements of the history of science are few. Anderson and colleagues (2011) describe a museum workshop about the role of artefact analysis/manipulations on research and teaching in the history of science and technology. In this study students from university departments of education also addressed this subject during classroom coursework using Eotvos torsion balance, an instrument used to measure small gravitational variations. Students constructed three narratives related to the science of geodesy and discussed issues related to laboratory practice and the nature of science.

Falomo-Bernarduzzi and colleagues (2012) have developed activities related to Galileo's laboratory that are designed to take place either in the museum or in the school and explain that these

> activities do not 'incidentally' interest schools, because they happen to connect with the school curriculum, but they are thought out with each school for the school. These workshops give clues which are the starting points for classroom activities linked to the project but also part of normal school learning. (Falomo-Bernarduzzi et al. 2012)

The researchers describe projects that rely extensively on the history of science in a number of ways using primary and secondary sources, museum exhibitions, multimedia and hands-on reconstructions of historical experiments. More specifically, they present activities that are based on the exhibition 'Laboratorio di Galileo' which includes reproductions of the apparatuses designed and used by Galileo for his experiments in mechanics.

Finally, Paparou (2011) describes lecture-demonstration activities created and performed by teachers in the classroom using collections of scientific instruments from the local *Museum of History and Physics* of the first high school of Chios

Island (Greece). Examples of such lecture-demonstrations include ‘The first days of electricity’ and ‘The history of magnets and compasses’. During these programmes, participants were invited to observe and compare scientific instruments, conduct experiments and evaluate the experimental results, make explanatory hypotheses and explore historical scientific documents (Paparou 2011).

All the educational attempts that were discussed in the previous sections focus on the study of scientific instruments and experiments as tools for educating students and teachers about history of science issues in the context of collaboration between museums and formal education institutions. It is apparent that such a collaboration can play a seminal role in evaluating and transforming scientific collections (original/historical collections, digital collections or collections of reconstructed instruments) from tools of research to tools of education (Heering 2011).

49.5 Conclusion

The variety of reviews that refer to the introduction of elements of history of science in primary and secondary school (Matthews 1994/2014; Duschl 1994; Seroglou and Koumaras 2001; Hottecke and Silva 2010) indicates the systematic and continuous involvement of historians of science and science educators with the issue of introducing elements from the history of science into formal science education. In contrast, as the present review has shown, the study of the role of the history of science in informal and non-formal science education is heterogeneous and fragmentary. It is necessary to raise new research questions and construct new lines of research to investigate the subject in a more systematic way.

We have suggested three lines of research strands below:

(1) *The epistemological research strand.* This strand refers to those research questions primarily of interest to science museum professionals related to the role that history of science can play in the realisation of the communication and education objectives of museums. How and why can the history of science as presented through museum collections contribute to the rescue, preservation and diffusion of scientific heritage and culture at local, national and international levels? Lourenco (2012), for example, suggests that

> the increased interest by the historian of science creates opportunities for a more significant role of history in museums of science, potentially resulting in better documented collections, as well as more meaningful and contextualized exhibitions and educational programmes. However, more history in museums of science requires considerable structural and cultural changes in their traditional missions, roles and practices. (Lourenco 2012)

On the other hand, primary questions that in our opinion should concern science centres that aim at the diffusion and popularisation of modern scientific knowledge are the following: Is it possible, and if so, how could the history of science contribute to reducing the ever-growing gap between the production of scientific knowledge and its understanding by lay people? How could the history of science contribute to restorating the relationship between science and culture that has increasingly soured since the early twentieth century? (Bensaude-Vincent 2001; Lévy-Leblond 2004). Is it possible to incorporate the narrative of the history of scientific ideas into the narrative of the modern world and its relationship to contemporary society, or should they be considered two epistemologically incompatible narratives? These questions are also interrelated to the following research strand.

(2) *The museological/museographical research strand.* This strand is mostly related to the way in which science museums take into account the history of science and translate it into a communication and educational tool to achieve their educational mission. Historians of science, museologists and possibly science educators need to collaborate towards that end. Referring to collections and exhibitions of the *Science Museum* in London, Bud (1997) noted that

> before the Second World War the progressivism of the galleries and the inspiration of its greatest icons mostly matched the views of academics. However, the post-war years, which saw an efflorescence of paper-based historiography of science, saw too a decoupling between the interests of academics interested in intellectual process and of curators focused upon their objects. This decoupling meant that the history of science of which the Museum was the public space, was somewhat distanced from the burgeoning academic discipline. (pp. 50–51)

Bud makes clear that exhibitions of science act as important means of transformation of scientific knowledge, scientific and social practices and authentic objects to content, exhibits and forms of display, so that they could be successfully communicated to broader audiences. The concept of ‘mediating transposition’ used by Guichard and Martinand (2000) and the ‘museographic transposition’ used by Simonneaux and Jacobi (1997) constitute a proper context in which exhibitions that introduce elements of history of science used in combination with contemporary communication strategies and museographical techniques could be analysed or designed. In this context, further research questions could be posed in the following broad areas: (a) in relation to the deconstruction and reconstruction of a historical subject in science and the identification of possible related misconceptions often found in exhibitions (i.e. epistemological analysis, see Foss Mortensen 2010) and/or (b) the decoding and recoding of messages, if we regard exhibitions as pedagogical multi-modal texts (i.e. semiotic analysis, see Anyfandi et al. 2010).

(3) *The learning/pedagogical research strand.* In this noteworthy heterogeneous strand, the main issue is the investigation of learning in informal and non-formal settings and more particularly if and how cognitive progress of visitors is achieved during a science museum visit (e.g. Anderson et al. 2003; Martin 2004; Griffin 2004). Can history of science maximise visitors’ learning best when designed as a communicational element or as an educational tool? Is it better to use the history of science so that museum visitors can construct understandings of the nature of science and of conceptual elements of science? Studies addressing such questions can inform researchers in the fields of psychology and science education as well as designers of science exhibitions who seek to develop

a museological/museographical approach that maximises visitor learning. An important dimension of this research strand is developmental studies that investigate possible correlations between student learning of the official school programme and the coordinated activities that take place in schools and museums conjointly. In addition, existing didactic models that investigate how the introduction of elements of the history of science into formal education influence students' cognitive progress (e.g. Monk and Osborne 1997; Hottecke et al. 2012) could be altered to include activities in museum settings.

A necessary precondition for the establishment of the above-mentioned research strands is the acceptance of the strong transdisciplinary and interdisciplinary nature of this research and the creation of a collegial environment among the researchers involved. In other words, we need to accept that the intersection of the history of science, scientific museology and science education represents a fruitful set for the consideration of the theoretical background, the methodological approach and the social practices of science learning.

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Part XI
Theoretical Studies: Science, Culture and Society

Chapter 50
Science, Worldviews and Education

Michael R. Matthews

Karl Marx, in the opening of *The Eighteenth Brumaire of Louis Bonaparte,* famously wrote that:

> Men make their own history, but they do not make it just as they please; they do not make it under circumstances chosen by themselves, but under circumstances directly found, given and transmitted from the past. (Marx 1851, p. 595)

Marx's appreciation of the way in which human life – its engagements, politics, culture and economic practices – is shaped by circumstances, and in turn how lives act and transform those circumstances, is a quite general claim that applies also to scientific engagements and practices. Science, broadly speaking, is the effort of people and societies to identify, understand and 'make sense of' the objects and processes in the world around them; to tabulate the properties of natural things and processes; to ascertain what and how causal mechanisms in the world operate; and to achieve some degree of predictive certainty about the course of events and some degree of control over them. Science is conducted by people living in societies in specific historic stages of scientific, philosophical, intellectual (including mathematical), religious, technological, economic and cultural (including ethical and artistic) development. All of these elements bear upon scientists and upon the science they conduct; these elements both limit and put constraints on science and also enhance it. In turn, science bears upon these circumstances: sometimes strengthening, other times modifying, sometimes overthrowing or negating different of these domains. The history of these interactions provides grounds for identifying how some scientific traditions are better than others at achieving their goal of understanding and effectively intervening in the natural world; the history allows some lessons to be learnt about the kinds of social and cultural circumstances that allow

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The present chapter draws on Matthews (2009a, b, c) and on contributions to Matthews (2009d).

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science and scientists to flourish and conversely the circumstances that inhibit and curtail scientists and limit the scientific endeavour.

50.1 Science and Culture

Science, formerly ‘natural philosophy’, has always been a dynamic part of culture; it is affected by culture and has effects on culture; thus, science and worldviews (or *Weltanschauung*)[1] are interrelated, and a good science education should give students some appreciation of this interrelationship.[2] The educational value of such appreciation was recognised by the American Association for the Advancement of Science in its *Project 2061* publication where it said:

> … Becoming aware of the impact of scientific and technological developments on human beliefs and feelings should be part of everyone’s science education. (AAAS 1989, p. 173)

The position was elaborated a year later in its *The Liberal Art of Science*:

> The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues. (AAAS 1990, p. xiv)

These expectations found their way through to the US National Science Education Standards where there was a separate content strand on ‘History and Nature of Science Standards’ (NRC 1996) that affirmed:

> Students should develop an understanding of what science is, what science is not, what science can and cannot do, and how science contributes to culture. (NRC 1996, p. 2)

And

> The standards for the history and nature of science recommend the use of history in school science programs to clarify different aspects of scientific inquiry, the human aspects of science, and the role that science has played in the development of various cultures. (NRC 1996, p. 107)

Hugh Gauch, an agricultural scientist, wrote the lead essay in a recent volume of *Science & Education* (vol.18, nos.6–7, 2009) dedicated to *Science, Worldviews and Education* where he averred that questions about science’s relation to worldviews, either theistic or atheistic ones, are among the most significant of contemporary issues for scientists, science teachers and culture more generally (Gauch 2009). Many people are vitally interested in questions such as whether God exists, whether the world has purpose, whether there are spiritual entities that have causal influence on the world, whether humans have spiritual souls which distinguish them from

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[1] The German expression for ‘world outlook’ is more directly connected to feelings, ethics and personal and political action than the more passive Anglo term ‘worldview’.

[2] A classic account of the history of these interactions is J. D. Bernal’s four volume study *Science in History* (Bernal 1965). See also Crombie (1994), Dewitt (2004), and Randall (1962).

the animal world, whether the world is such that prayers can be answered and natural causal processes interrupted and so on. It is surely important for students and teachers to know if science can give answers, one way or the other, to these questions, or whether science is necessarily mute on the matters. Presumably knowledge of the nature of science should shed some light on whether science can or cannot answer such questions. Gauch surveys opinions of scientists, philosophers and educators and, predictably, finds disagreement within each group on the question of the legitimate purview of science.

Importantly Gauch carefully reports what position papers of the American Association for the Advancement of Science (AAAS) and the US National Research Council (NRC) say about the defining characteristics of science and thus what they say about worldviews and science. He identifies seven 'pillars' of the scientific enterprise that the AAAS and the NRC endorse. These are:

Pillar P1: *Realism.*	The physical world, which science seeks to understand, is real.
Pillar P2: *Presuppositions.*	Science presupposes that the world is orderly and comprehensible.
Pillar P3: *Evidence.*	Science demands evidence for its conclusions.
Pillar P4: *Logic.*	Scientific thinking uses standard and settled logic.
Pillar P5: *Limits.*	Science has limits in its understanding of the world.
Pillar P6: *Universality.*	Science is public, welcoming persons from all cultures.
Pillar P7: *Worldview.*	Science, hopefully, contributes to a meaningful worldview.

Gauch sees these seven pillars as, in part, amounting to the popular view that investigation of the supernatural lies outside of the domain of science; this is the widely held 'nonoverlapping magestria' (NOMA) position put forward by the late Stephen J. Gould (1999). But Gauch also finds an inconsistency with the AAAS position because at the same time the AAAS asserts that 'we live in a directional, although not teleological, universe'. For Gauch this is a denial of the fundamental worldview of the Judaic-Christian-Islamic traditions for which the world is neither purposeless nor ultimately unguided; and it is thus a statement that, contra NOMA, science is not worldview independent. He advances and defends the related thesis that:

> Science is worldview independent as regards its presuppositions and methods, but scientific evidence, or empirical evidence in general, can have worldview import. Methodological considerations reveal this possibility and historical review demonstrates its actuality. (Gauch 2009, p. 679)

The following fundamental questions arise for science teachers and curriculum writers and have been addressed by educators and by historians and philosophers of science:

What constitutes a worldview?
How do worldviews impinge upon and in turn be modified by ontological, epistemological, ethical and religious commitments?
What worldview commitments, if any, are presupposed in the practice of science?
What is the overlap between learning about the nature of science (NOS) and learning about worldviews associated with science?

What is the legitimate domain of the scientific method? Should scientific method be applied to historical questions, especially to historical questions concerning scriptures and sacred texts?
To what extent should learning about the scientific worldview be a part of science instruction?
Should science instruction inform student worldviews or leave them untouched? Should students be just 'border crossers' moving from their own culture with its particular worldviews to the science classroom in order to 'pick up' instrumental or technical knowledge and then back to their 'native' culture without being affected by the worldviews and outlooks of science?
What judgement do we make of science education programmes where the scientific view of the world is not affirmed or internalised but only learnt for instrumental or examination purposes, where learning science is akin to an anthropological study where students are not expected to believe or adopt what they are learning but merely be able to manipulate formulae and give correct answers on exams?

50.2 Science, Philosophy and Worldviews: Some Historical Developments

The celebrations in 2009 of the 150th anniversary of the publication of Darwin's *The Origin of Species* generated wide recognition of the interplay of science, culture and worldviews. Internationally – by dint of popular journals, academic symposia, newspaper articles, museum displays, books and television documentaries – the general public came to see what scholars have long recognised, namely, that the *Origin* provided not just a novel account of the origin of species by natural selection but it initiated a transformation of modern worldviews and a new understanding of the place of human beings in the natural world.[3] Versions of Darwin's evolutionary naturalism, reinforced and strengthened by modern genetics,[4] have entered into most modern worldviews, excepting those of many Christian fundamentalists, many Muslims and many indigenous cultures.[5]

Earlier in 2005 with the celebration of the centenary of Einstein's *annus mirabilis*, the public also saw and appreciated the contribution of science to worldviews. People knew, perhaps less clearly and dramatically than with Darwin, that something important began to happen in 1905 with the publication

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[3] A 2013 Richard Attenborough television documentary series, 'The Galapagos Islands', is promoted as 'The islands that transformed our view of life on earth'.

[4] Learning that that *Homo sapiens* shares 98.4 % of its genes with pygmy chimpanzees can change a person's views of their relationship to the animal world.

[5] Of the voluminous literature on Darwinism and worldviews, see especially Dennett (1995, 2006), Greene (1981), McMullin (1985), and Ruse (1989).

of Einstein's three papers, even if few understood the details and could share the opinion of the physicist-philosopher Fritz Rohrlich that:

> The development of quantum mechanics led to the greatest conceptual revolution of our century and probably to the greatest that mankind had ever experienced. It most likely exceeded the great revolutions in our thinking brought about by the Copernican revolution, the Darwinian revolution, and the special as well as the general theory of relativity. Quantum mechanics forced us to reconsider our deepest convictions about the reality of nature. (Rohrlich 1987, p. 136)

Although Darwin and Einstein are the most recent and most widely known cases of science impacting on philosophy and culture, these impacts go right back to the very cradle of Western natural philosophy; there has been a continuous interaction between science, philosophy, metaphysics and ultimately worldviews. The 'science' (natural philosophy) of the classical and Hellenic materialists and atomists – Thales, Anaximander, Leucippus, Democritus, Epicurus, Anaxagoras and others – was in constant struggle with the dualist, teleological philosophy and purposeful worldviews of Platonists and Aristotelians. Karl Popper (Popper 1963, Chap. 5) drew attention to this 'struggle' between the early naturalist and materialist scientific tradition among the pre-Socratics and its dualist, teleological, philosophical opponents, chiefly Plato and Aristotle. The latter pair won, and the former group were for nearly 2,000 years relegated to being just 'pre-Socratics' or the philosophical 'warm-up' or targets for the main Athenian adventure. But to a small extent, their reputation has been recovered, with one representative historian of Greek philosophy writing of the Atomists Leucippus and Democritus that:

> In their atomism, their theory of motion, their distinction between primary and secondary qualities, and most of all, in their insistence that explanation of natural processes shall be mechanical, the atomists anticipated much in the world view of modern science. (Allen 1966, p. 15)

Anaximander's explanation of thunder as noise created not by heavenly Gods or spirits but by the rubbing together of wind particles well represents the division between materialist or naturalist explanatory systems and 'pre-scientific' ones.[6]

For Popper, and many others, the Scientific Revolution was a 'return to the past', a recapturing of materialist ontology and non-teleological causal relations.[7] Wallis Suchting has described these struggles in the cradle of Western science and philosophy as:

> Despite all the differences between Plato and Aristotle the latter carried on the work of the former in essential ways, like that of offering a metaphysical 'foundation' for the sciences and a teleological view of the world. Christianity took up elements of Platonic thought … but, its philosophical high-point, in Thomism, mainly appropriated Aristotle. Atomism carried on a basically marginal existence, … till it was recuperated by Galileo. (Suchting 1994, p. 45)

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[6] Benjamin Farrington's *Science and Politics in the Ancient World* (1939) is a classic treatment of these themes.

[7] See especially Blumenberg (1987), Mittelstrass (1989), Solmsen (1960), Stove (1991), and Vitzthum (1995, Chap. 2).

The Scientific Revolution of the seventeenth century occurred in a Europe whose cultural, scholarly and religious life was permeated by Aristotelian philosophy, by convictions about ontology, epistemology, ethics and theology that were informed and judged by the texts of Aristotle. Neo-Aristotelian Scholasticism, although not monolithic in its interpretation of Aristotle,[8] dominated medieval and Renaissance universities.[9] Scholastic philosophy was intimately connected with the Catholic Church, but it also held sway in Protestant seminaries and universities (Dillenberger 1961, Chap. 2). As one commentator has observed:

> The Middle Ages mean simply the absolute reign of the Christian religion and of the Church. Scholastic philosophy could not be anything else than the product of thought in the service of the reigning *Credo*, and under the supervision of ecclesiastical authority. (De Wulf 1903/1956, p. 53)[10]

In Aristotelian-informed Scholastic ontology, things were constituted by form and by matter; this was the doctrine or principle of hylomorphism; it was fundamental to the Aristotelian tradition. Frederick Copleston has rightly noted that Aquinas, the greatest of the Scholastics,[11] 'took over the Aristotelian analysis of substance' (Copleston 1955, p. 83) and:

> According to Aquinas, therefore, every material thing or substance is composed of a substantial form and first matter. Neither principle is itself a thing or substance; the two together are the component principles of a substance. And it is only of the substance that we can properly say that it exists. 'Matter cannot be said to be; it is the substance itself which exists'. (Copleston 1955, p. 90)

It was the 'New Science' that led eventually to the unravelling of this settled medieval philosophical-theological worldview. This began with the publication in (1543) of Copernicus's astronomical work *On the Revolution of the Heavenly*

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[8] The varieties of medieval and renaissance Aristotelianisms arose from efforts to accommodate ever new developments and discoveries in natural philosophy. See Blum (2012) and Schmitt (1983).

[9] A classic work on the doctrines and history of Scholastic philosophy is De Wulf (1903/1956). See also volumes two and three of Frederick Copleston's *History of Philosophy* (Copleston 1950). Etienne Gilson and Jacques Maritain are the best-known twentieth-century exponents of Scholasticism.

[10] Sadly this description, *sans* Church, fitted philosophy departments in most of the former communist states and philosophy departments China where 'Marxist Dialectics' is still a compulsory subject. It is also the situation of philosophy departments in many Islamic states where all philosophical positions in ontology, epistemology and ethics need to conform to state-sanctioned interpretations of the Koran. According to Sheikh Muhammed Salih Al-Munajjid, a known Islamic lecturer and author: 'hence philosophy, as defined by the philosophers, is one of the most dangerous falsehoods and most vicious in fighting faith and religion on the basis of logic, which it is very easy to use to confuse people in the name of reason, interpretation and metaphor that distort the religious texts'. In such Marxist and Islamic regimes, philosophy simply cannot be practised; the regimes are replicating at a state level what the Roman Catholic Church used maintain at a seminary level, namely, rigorous thought control.

[11] On the life and philosophy of Aquinas, see Copleston (1955), Gilson (1929), Kenny (1980), and Weisheipl (1974).

Spheres (Copernicus 1543/1952).[12] But it was almost a century later that the unravelling took dramatic shape with the publication in 1633 of Galileo's *Dialogues Concerning the Two Chief World Systems* followed 50 years later by Newton's *Principia Mathematica*. These two books, separated by a mere 50 years, embodied the intellectual core of the Scientific Revolution; they constituted the Galilean-Newtonian Paradigm, a GNP far more influential than any economic GNP has ever been.

The 'New Science' established the Copernican heliocentric account of the solar system which removed humans from their religiously and culturally privileged place in the centre of the universe; it introduced a mechanical and lawful account of natural processes; it challenged and in many places overthrew the long dominant Aristotelian philosophical system that was, among other things, intimately tied up with Roman Catholic theology and ethics; and famously the GNP caused a reassessment of the role of religious authority in the determination of claims about the world and indeed in any claims.[13]

The new science (natural philosophy) of Galileo, Descartes, Huygens, Boyle and Newton caused a massive change not just in science but in European philosophy that had enduring repercussion for religion, ethics, politics and culture. Early modern philosophers –from Francis Bacon, Thomas Hobbes, John Locke, David Hume, George Berkeley, René Descartes, Gottfried Leibniz up to Immanuel Kant – were all engaged with and reacting to the breakthroughs of early modern science,[14] as of course were the later philosophers of the French, English, German and Scottish Enlightenment; seventeenth-century science was the seed that bore eighteenth-century philosophical and worldview fruit. With the inevitable exceptions and qualifications required when talking of any large-scale transformation or revolution in thought, it can be said that all the major natural philosophers of the time rejected Aristotelianism in their scientific practice, their theorising and in their enunciated philosophy. Overwhelmingly the new philosophy to which they turned was corpuscularian, mechanical and realist – it has rightly been called the 'mechanical worldview'.[15]

In this new worldview, there was simply no place for the entities that Aristotelianism utilised to explain events in the world: Hylomorphism, immaterial substances, unfolding natures, substantial forms, teleological processes and final

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[12] For the background, context and impact of Copernicus, see Blumenberg (1987), Gingerich (1975, 1993), and Grant (2004).

[13] A classic discussion is Dijksterhuis's *The Mechanization of the World Picture* (1961/1986). On the wider impact of the Galilean-Newtonian method, see Butts and Davis (1970), Cohen (1980), McMullin (1967), and Shank (2008).

[14] Unfortunately these early modern philosophers are frequently studied in isolation from the contemporary science with which they were engaged; early modern philosophy is presented to students as a drawn-out soliloquy, not the dialogue and debate with early modern science that it was. This theme, with texts, is developed in Matthews (1989a).

[15] For historical and philosophical elaboration of the mechanical world view, see Dijksterhuis (1961, 1961/1986), Einstein and Infeld (1938/1966), Hall (1954/1962), Harré (1964), Hatfield (1990), and Westfall (1971).

causes were all banished from the philosophical firmament. René Descartes aptly sums up the new philosophy in the conclusion of his *Principles of Philosophy* (1659) with a clear statement of the new corpuscularian philosophy:

> Nor do I think that anyone who uses his reason will deny that we do much better to judge of what takes place in small bodies which their minuteness alone prevents us from perceiving, by what we see occurring in those that we do perceive [and thus explain all that is in nature, as I have tried to do in this treatise], than, than in order to explain certain given things, to invent all sorts of novelties, that have no relation to those that we perceive [such as are first matter, substantial forms, and all the great array of qualities which many are in the habit of assuming, any of which it is more difficult to understand than all the things which we profess to explain by their means]. (*Principles* Bk.IV, art.101; Haldane and Ross 1931, pp. 297–298)

A foretaste of the coming mechanical worldview can be found in Galileo's distinction between, what will come to be called, the primary and secondary qualities of bodies. Seventy years later, his distinction was repeated by Robert Boyle and was famously articulated by John Locke,[16] and it has had an enduring presence in the subsequent history of Western philosophy. The distinction was at the heart of Galileo's theory of matter, a theory that answers such basic ontological questions as: Of what is matter constituted? And, what are the inherent and necessary properties of matter?[17]

For Aristotle and the Scholastics, matter was ultimately of the one stuff – 'prime matter' – gold, silver, timber, did not differ in their ultimate material; they just differed in how this material was arranged and what forms animated it. For this philosophical tradition, the properties or qualities of bodies were real. Colour, heat and odour belonged to bodies; the quality was a quality of the body. Heated red bodies *were* hot and they were red. These qualities are perceived by the senses, not generated by the senses. Aristotelians were realists, not subjectivists, about qualities.

In contradiction to this, Galileo reached back to pre-Socratic atomistic sources and to more recent medieval nominalist sources, for his account of matter. As a student he had read Democritus, Lucretius and possibly other early atomists such as Leucippus the teacher of Democritus. For them colour and taste were opinions, mere names; what existed in the world was atoms and the void, and atoms had neither colour nor taste. They held a material monist position – all matter was an aggregate of invisible and indivisible 'atoms' each of which was made of the same material and differing among themselves only in size and shape. It was the particular aggregate of atoms that gave bodies their tangible properties; a body's properties were not produced or caused by its form. When new substances are created from different materials, their immutable atoms are just rearranged in different ways; there is no change of form, because there was no form to change. This atomistic ontology was so comprehensively rejected by Aristotle in this *Physics* and his *Metaphysics* that it disappeared from the philosophical firmament for over a

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[16] See Locke's *Essay Concerning Human Understanding* Book II Chap. 8 (Locke 1689/1924, pp. 64–73).

[17] On ancient, medieval and modern theories of matter, see contributions to McMullin (1963a, b).

thousand years until it was revived by some thinkers on the margins of medieval philosophy such as William of Ockham and Nicholas of Autrecourt.

Galileo's atomism is first and most famously stated in his *The Assayer* (Galileo 1623/1957) where he advances invisible 'atomic' motions as the cause of heat. He says:

> But first I must consider what it is that we call heat, as I suspect that people in general have a concept of this which is very remote from the truth. For they believe that heat is a real phenomenon, or property, or quality, which actually resides in the material by which we feel ourselves warmed. (Galileo 1623/1957, p. 274)

Galileo makes explicit his atomism, or corpuscularianism, when he says:

> Those materials which produce heat in us and make us feel warmth, which are known by the general name of 'fire', would then be a multitude of minute particles having certain shapes and moving with certain velocities. Meeting with our bodies, they penetrate by means of their extreme subtlety, and their touch as felt by us when they pass through our substance is the sensation we call 'heat'. … I do not believe that in addition to shape, number, motion, penetration, and touch there is any other quality in fire corresponding to 'heat'. (ibid)

Galileo believed that it was the shape, size, motion and collisions of minute, unseen 'atoms' or corpuscles that determined all outward and perceivable states, processes and phenomena. This was his restatement of ancient atomism. Galileo's ontology was simply inconsistent with Scholastic metaphysics and thus with the medieval worldview built upon it. Galileo's distinction between primary and secondary qualities was the beginning of the unravelling of this 'Medieval Synthesis' and its replacement by the 'mechanical' or 'corpuscularian' worldview and ultimately the 'scientific' worldview.

Newton, the greatest of all seventeenth-century scientists, was also a champion of the New Philosophy.[18] Beginning in his student days, Newton embraced Galileo's mathematical methods, his Copernicanism, his experimentalism, his rejection of Aristotle's physics, his rejection of Scholastic philosophy and his embryonic atomism.[19] In the Preface of the *Principia*, Newton identifies himself with the 'moderns, rejecting substantial forms and occult qualities' and endeavours 'to subject the phenomena of nature to the laws of mathematics' (Newton 1729/1934, p. xvii).

In keeping with Boyle's example of experimentally testing and utilising metaphysical positions, Newton in his *Opticks* gave an atomistic account of light and optical phenomena (Newton 1730/1979). After 300-odd pages of optical experiments and investigations, Newton in Query 29 of Book III says:

> Are not Rays of Light very small Bodies emitted from shining Substances? For such Bodies will pass through uniform Mediums in right Lines without bending into the Shadow, which is the Nature of Rays of Light. They will also be capable of several Properties, and be able

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[18] Numerous works are available on Newton's philosophy and metaphysics, among them are Hughes (1990), McGuire (1995), McMullin (1978), and Stein (2002). Although an atomist, Newton distanced himself from Descartes' interpretation of the theory.

[19] For Newton's early scientific and philosophical formation, see Herivel (1965) and Westfall (1980, Chaps. 3,4,5)

> to conserve their Properties unchanged in passing through several Mediums which is another Condition of the Rays of Light. (Newton 1730/1979, p. 370)

Much can be said about atomism, its recovery by philosophical contemporaries of Galileo such as Francis Bacon and Pierre Gassendi and its role in the Scientific Revolution, but for current purposes it suffices to repeat Craig Dilworth's judgement that:

> The metaphysics underlying the Scientific Revolution was that of early Greek atomism. … It is with *atomism* that one obtains the notion of a *physical* reality underlying the phenomena, a reality in which *uniform causal* relations obtain. … What made the Scientific Revolution truly distinct, and Galileo … its father, was that for the first time this empirical methodology [of Archimedes] was given an ontological underpinning. (Dilworth 2006, p. 201)

And the role of the New Science in generating the modern worldview is well stated by Herbert Butterfield[20]:

> Since that revolution overturned the authority in science not only of the middle ages but of the ancient world – since it ended not only in the eclipse of scholastic philosophy but in the destruction of Aristotelian physics – it outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of … mere internal displacements … it changed the character of men's habitual mental operations even in the conduct of the non-material sciences, while transforming the whole diagram of the physical universe and the very texture of human life itself. (Butterfield 1957, p. 7)

When Butterfield writes of the New Science changing 'the character of men's habitual mental operations', he is speaking of what the AAAS will later call the 'scientific habit of mind' (Rutherford and Ahlgren 1990, Chap. 12) and what Jawaharlal Nehru and the drafters of the Indian Constitution called for in promoting a 'scientific temper'.[21] Effects on a society's 'mental operations', 'habits of mind' or 'scientific temper' depend on citizens learning about and valuing science, on having a worldview where such ways of thinking can be exercised, and hence ultimately on effective and widespread science education.

50.3 From Science to Heresy: The Catholic Church's Condemnation of Atomism

The worldviews of science and of religion do not always sit easy with each other; accommodations usually need to be made. In recent times, worldview conflicts occasioned by disputes about Creation, Creationism, Teleology, Miracles, the

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[20] There is a vast literature on the Scientific Revolution, including a debate on whether to capitalise the terms; an informative guide to the different assessments, literature and debates is H. Floris Cohen's *The Scientific Revolution* (Cohen 1994).

[21] The 1948 Indian Constitution makes obligatory the state's 'promotion of scientific temper' among its citizenry, not just scientific knowledge but scientific outlook or habits of mind (Haksar 1981).

existence of souls and spirits and so on have moved from academic corridors to the public domain with bestsellers (Dawkins 2006; Dennett 1995), television programmes, public debates and countless scholarly articles devoted to explicating or defending one side or other of these conflicts.[22]

Many of the major seventeenth-century contributors to the new science – Galileo, Descartes, Boyle and Newton – were believers, although in somewhat tense relations with their respective established churches (Roman Catholic for the first two, Anglican for the second two). Some believers rejected the new science; some wanted the new science but not its associated metaphysics; and some, such as Joseph Priestley, embraced both the new science and its atomistic metaphysics and adjusted their religious ontology accordingly. When the seventeenth-century natural philosophers and the Enlightenment philosophers of the eighteenth century stressed the materialism, mechanism and determinism of the new science, they brought upon themselves the ire of most contemporary religious figures who saw the emerging new worldview as anti-Christian and atheistic.[23] The historian Richard Westfall well summarises the general situation:

> Natural science rested on the concept of natural order, and the line that separated the concepts of natural order and material determinism was not inviolable. The mechanical idea of nature, which accompanied the rise of modern science in the 17th century, contradicted the assertion of miracles and questioned the reality of divine providence. Science, moreover, contained its own criteria of truth, which not only repudiated the primacy of ancient philosophers but also implied doubt as to the Bible's authority and regarded the attitude of faith enjoined by the Christian religion with suspicion. (Westfall 1973, pp. 2–3)

And Westfall proceeds to say:

> every one of the problems could be resolved in a variety of ways to reconcile science with religion. But the mere fact of reconciliation meant some change from the pattern of traditional Christianity (ibid)

These 'grand historic' reconciliations are repeated at the personal level for many science students.

Although Galileo was, in 1615, warned not to hold or teach the Copernican doctrine of a moving Earth, it was only after *The Assayer* and its endorsement of atomism was published in (1623) that he faced serious theological charges. There was a move by opponents from general disquiet to specific repudiation.

Atomism presented particular and grievous problems for Christian belief, but the most basic and important one was the central Roman Catholic, Greek Orthodox and Eastern Uniate teaching on Christ's presence in the Eucharist, the doctrine of Transubstantiation. The Eucharist was the sacramental heart of the Catholic Mass, and the Mass was and is the devotional heart of the Church. Belief in the Real Presence of Christ, brought into being by the priest's consecration of the communion host, underwrites devotional practice and doctrinal authority. Denial of the Real

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[22] See Michael Ruse (2011) for one informed account of these debates and also the careful review of this book by Peter Slezak (2012).

[23] See, for instance, Brooke (1991, Chap. V), Israel (2001), and Porter (2000).

Presence was a capital offence. It was a litmus test in the Inquisition, where failure to affirm the belief meant a horrible death at the stake.

Scholastic philosophy, with its Aristotelian categories of substance, accidents and qualities, could bring a modicum of intelligibility to this central mystery of faith, as it could also bring a modicum of intelligibility to doctrines such as the Incarnation, the Trinity, and immortality of the soul. Scholasticism held that at consecration the substance of bread changed to the substance of Christ's body, but the accidents remained that of bread. So Christ became truly present, even though no sensible, observable change was apparent.

Thomas Aquinas formulated the orthodox doctrine as:

> All the substance of the bread is transmuted into the body of Christ… therefore, this is not a formal conversion but a substantial one. Nor does it belong to the species of natural mutations; but, with its own definition, it is called transubstantiation. (*Summa Theologica* III, q.75, a.4, in Redondi 1988, p. 212)

This Thomist formulation, along with the Aristotelian philosophical apparatus required for its interpretation, was affirmed as defining Catholic orthodoxy at the Council of Trent in 1551.

The nature of the heresy charges against Galileo, and the degree to which atomism was at odds with established religiosity and theology, can be seen in a condemnation brought anonymously by Father Giovanni de Guevara, a Vatican confidant of Pope Urban VIII. Guevara was a priest of a contemplative order whose very life revolved around adoration of the Eucharistic sacrament. He had minimal philosophical training but enough to see the conflict between Galileo's atomistic position and the orthodox interpretation of the Real Presence – for Guevara they could not both be true (Redondi 1987, pp. 166ff). In his 1624/1625 deposition he charged that:

> [Galileo's position] is in conflict with the entire community of Theologians who teach us that in the Sacrament remain all the sensible accidents of bread, wine, color, smell, and taste, and not mere words, but also, as is known, with the good *judgment* that the quantity of substance does not remain. (Redondi 1987, pp. 333–334)[24]

The charge of atomism against Galileo, with its direct implications of heresy, was made in 1626 by Father Grassi, a prominent Jesuit professor of mathematics and astronomy at the Collegio Roman. Grassi made clear the gravity of the philosophical point by adding that transubstantiation 'constitutes the essential point of faith or contains all other essential points' (Redondi 1987, p. 336).[25] Descartes' matter theory was likewise condemned in 1671 because its categories did not allow an intelligent rendering of the doctrine of Transubstantiation.

John Hedley Brooke, an historian sympathetic to the positive contribution of religion to science, recognised the problem that atomism posed 'especially for the

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[24] A translation of the deposition, and discussion, is also available in Finocchiaro (1989, pp. 202–204).

[25] This contention echoed through all Catholic teaching and devotional practice; as one Catholic Handbook states the matter: 'The Catholic belief is that the sacrifice of the Mass is the sacrifice of the body and blood of Christ *under the form of bread and wine*' (Lucey 1915, p. 93).

Roman Catholic Church, which took a distinctive view of the presence of Christ at the celebration of the Eucharist' (Brooke 1991, p. 141). He writes:

> With an Aristotelian theory of matter and form, it was possible to understand how the bread and wine could retain their sensible properties while their substance was miraculously turned into the body and blood of Christ. …. But if, as the mechanical philosophers argued, the sensible properties were dependent on an ulterior configuration of particles, then any alteration to that internal structure would have discernible effects. The bread and wine would no longer appear as bread and wine if a real change had occurred. (Brooke 1991, p. 142)

50.4 The Decline of Atomism: Scientific or Philosophic Causes?

No sooner had Newton ceased writing than the philosophy of atomism, and its associated mechanical worldview was augmented and modified. This history is a case study of the relation between science and metaphysics: To what extent did the metaphysics change for philosophical reasons and to what extent did it change for scientific reasons?[26] To the scientific ontology of atoms and the void there was added, after considerable struggle, attractive and repulsive forces. Leibniz famously denounced Newton's attractive forces because he thought they reintroduced Scholastic occult entities to the ontology of natural philosophy (Hall 1980). In the nineteenth century, to this expanded scientific ontology were added magnetic and electric fields. The formulation of electromagnetic field theory by Maxwell, Boltzmann and Hertz fully stretched, and then ruptured, the atomistic ontology; and the energeticist interpretation of thermodynamics had the same result; and at the end of the century Mach, for example, abandoned atoms and denounced the atomic hypothesis as metaphysics.[27] This then provided the full range of scientifically legitimate explanatory and causal entities, at least until the advent of quantum theory.

The expansion of the ontology of science is a case study in the interaction of science and metaphysics. The atomists held on *philosophical* grounds that all legitimate explanation had ultimately to be in terms of the properties of atoms and of their movements and interactions. Their science was constrained by their philosophy. Clearly the addition of forces and fields to the class of existent things was not done on philosophical grounds but on *scientific* grounds; it seemed that only recourse to the latter entities enabled consistent scientific explanation and progress.

This expanded ontology was inconsistent with the metaphysics of *physicalism*: Forces and fields did not have mass; they could not be bumped into; and they had no

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[26] On the history of atomism and its connections with science on the one hand and with philosophy on the other, see Chalmers (2009), Pullman (1998), and Pyle (1997). An older historical study that concentrates more on the philosophical side of atomism is Melsen (1952).

[27] There are many good accounts of the modification, and eventual breakdown, of the mechanical worldview. See especially Einstein and Infeld (1938, Chap. 2), Harman (1982, Chap. 6), Hesse (1961), and McMullin (1989).

colour. They were not physical objects, the things that physicalism maintained were the only kinds of existing entities. It was also inconsistent with *materialism* in as much as this philosophy maintained that all entities with causal powers were material.[28] But the enriched ontology was consistent with *naturalism*, the view that only those kinds of entities exist that science reliably demonstrates as having consistent, causal and explanatory power. Thus things can be natural while not physical or material. The Mechanical Worldview survived the demise of atomism: There were still pushes and pulls, nature was not unfolding Aristotelian-like from within, but the deterministic pushes and pulls were no longer just those of colliding bodies, but gravitational and electric forces were added (Westfall 1971).

50.5 Philosophy as the Handmaiden of Theology and of Other Systems

Joseph Priestley, one of the luminaries of the British Enlightenment and a lifelong Christian believer, well expressed the ill ease felt about cloaking Christian doctrine in Scholastic clothes. In 1778 he wrote to the Jesuit 'materialist' philosopher Abbé Roger Boscovich saying that:

> the vulgar hypothesis [Aristotelian matter theory], which I combat, has been the foundation of the grossest corruptions of true Christianity; and especially [those] of the church of Rome, of which you are a member; but which I consider as properly *antichristian*, and a system of abominations little better than heathenism. (Schofield 1966, p. 167)

Despite such criticisms, the Catholic Church was guided by the medieval view that 'philosophy was the handmaiden' of theology; philosophy was to be subservient to religious and theological purposes. This was the import of the sixteenth-century Tridentine decrees and curial decisions right through to the twentieth century.[29] Pope Leo XIII promulgated his encyclical *AEterni Patris* that gave the name *philosophia perennis* (perennial philosophy) to Thomism and directed Catholic educational institutions to base their philosophical and theological instruction upon it. In 1914 Pius X issued his *Doctoris Angelici* decree, stating that:

> We desired that all teachers of philosophy and sacred theology should be warned that if they deviate so much as an iota from Aquinas, especially in metaphysics, they exposed themselves to grave risk. (Weisheipl 1968, p. 180)

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[28] On the history and philosophy of materialism, see Bunge (1981) and Vitzthum (1995).

[29] One hundred years *after* Priestley's complaints to Boscovich, Joseph McCabe, a former Franciscan priest and professor of philosophy who left the Church in the 1890s, well described the state of Roman Catholic theology when he said derisively of his theological training that:

> The various points of dogma which are contained (or supposed to be contained) in Scripture, were first selected by the Fathers, and developed, generally by the aid of the Neo-Platonic philosophy, into formidable structures. The schoolmen completed the synthesis with the aid of Peripatetic philosophy, and elaborated the whole into a vast scheme which they called theology. (McCabe 1912, p. 73)

A few years later, the *Code of Canon Law*, promulgated by Pope Benedict XV in 1917, reinforced the position by requiring that all professors of philosophy hold and teach the method, doctrine and principles of St Thomas. The papal endorsement of thirteenth-century philosophy continued through to 1950 when Pope Pius XII in *Humani generis* demanded that future priests be instructed in philosophy 'according to the method, doctrine and principles of the Angelic Doctor' (Weisheipl 1968, p. 183). It was only in the final years of the twentieth century, with Pope John Paul II's 1998 encyclical, *Fides et Ratio*, that the Catholic Church relaxed its attachment to Thomism as official Church philosophy. Thomism was downgraded from Absolute Truth to Highly Probable Truth.[30]

The Thomist tradition had enormous cultural and personal impact in Catholic Europe (especially Ireland, Portugal, Spain, Italy, Poland), Latin America,[31] the Philippines and elsewhere. For centuries Thomism was marshalled to support Church teaching on contraception, abortion, masturbation and homosexuality; where the Church exercised political power and influence, these teachings transferred into national law with the immoral acts becoming illegal and punishable by the State and not just for Catholics but for all citizens. In all cases the reason for condemnation was that the activity was 'unnatural', this whole conceptualisation coming from Aristotle's understanding of objects and actions as having natures which left alone unfolded 'naturally' and when interfered with unfolded 'violently' or 'unnaturally'.[32]

Clearly Thomism and Scholasticism and more generally Aristotelianism survived the Scientific Revolution; belief in the core metaphysical and ethical positions has survived to the present day.[33] Indeed neo-Aristotelianism is perhaps the most substantial and lively current of thought in contemporary ethical theory, with exponents such as Alasdair McIntyre, Elizabeth Anscombe and Martha Nussbaum all contributing substantial books to the Aristotle-sourced project of 'virtue ethics'. But the success of modern science has meant that Thomism in particular and Aristotelianism more generally has had to engage with science. Some have done this while preserving Aristotelianism (van Laer 1953, 1956; 1962; Maritain 1935/1951; Mascall 1956); for others the engagement has led to

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[30] On John Paul II's encyclical and how it reviewed and revised the status of Thomism, see Ernst (2006).

[31] Concerning early twentieth-century Thomist philosophy in Colombia, Daniel Restrepo wrote: 'To the extent that the Columbian State was governed by theocratic criteria, philosophy, conceived as "servant of theology", played the role of ideological mediator in the political action and principles of those who had held power since 1886' (Restrepo 2003, p. 144). Late into the twentieth century, passing 'Thomism I' was still a requirement for progression in many Latin American universities. Much like passing 'Dialectics I' is such a requirement in present day China.

[32] As an example of this reasoning and mindset, for Aquinas sexual intercourse was 'naturally ordained for procreation' (*Sentences* 4.31.2.2), so even indulging in coitus for reasons of health (a good purpose) nevertheless rendered the act unnatural and thus sinful as it was not done for its primary end. On all of this, see Noonan (1965, Chap. viii).

[33] See, for instance, arguments and literature in Ashley (1991) and Lamont (2009). The philosophy journal *New Scholasticism* was published from 1927 to 1989, *The Thomist* journal has been published continuously since 1939 and *The Modern Schoolman* has been published continuously since 1925. And of course numerous non-Anglo 'scholastic' philosophy journals are still published.

rejection in whole or part of Aristotelian philosophy.[34] This is a substantial example of the impact of science on philosophy and culture and of culture's responses and reactions to such impacts.

The same dynamics have played out in the Muslim world where the medieval view of philosophy as the servant of the Koran still holds. It is simply not possible for a Muslim to entertain or commit to any philosophical system that cannot be reconciled with the assumed ontology, epistemology and ethics of the Koran. The project of 'Islamisation of knowledge' is widely accepted as simply a part of Islam and of being a Muslim. Its purpose is to counter the humanistic and secular foundation of the Western education and culture, which it sees as based on five core principles:

1. The sovereignty of man, as though supreme (humanism)
2. Basing all knowledge on human reasoning and experience (empiricism)
3. Unrestricted freedom of thought and expression (libertarianism)
4. Unwillingness to accept 'spiritual' truths (naturalism)
5. Individualism, relativism and materialism

A representative Islamic appraisal of the Scientific Revolution is Seyyed Nasr's claim that the new science of Galileo and Newton had tragic consequences for the West because it marked:

> The first occasion in human history when a human collectivity completely replaced the religious understanding of the order of nature for one that was not only nonreligious but that also challenged some of the most basic tenets of the religious perspective. (Nasr 1996, p. 130)

Nasr repeats Western religious and Romantic criticisms of the new science when he writes:

> Henceforth as long as only the quantitative face of nature was considered as real, and the new science was seen as the only science of nature, the religious meaning of the order of nature was irrelevant, at best an emotional and poetic response to 'matter in motion'. (Nasr 1996, p. 143)

The engagement of philosophical systems with science has been especially urgent when the systems are tied to political and institutional power, as Thomism has been with the Roman Catholic Church. The same situation has applied with Marxism within the former Soviet state,[35] Maoism and dialectics in contemporary China,[36] Confucianism in Chinese history,[37] National Socialist philosophy in Hitler's

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[34] The survival of Thomism and the dynamics of its engagement with modern science is discussed in Matthews (2009b, pp. 718–720). In a recent publication, a neo-Aristotelian moves philosophy of science away from philosophising on the content of science to philosophical reflection on the activity of science (Marcos 2012).

[35] For 'official' philosophy in the Soviet Union and its contested relationship to science, see Graham (1973).

[36] 'Introduction to Dialectics of Nature (IDN)', based on Engels' book, was under Mao, a compulsory course for all Chinese graduate students. Under Xiaoping Deng, the course remained compulsory but in 1987 was rebadged 'Philosophy of Science and Technology (PST)' with the same IDN teachers. For the relationship of philosophy, politics and science in China, see Chan (1969) and Gong (1996).

[37] See Kwok (1965).

Third Reich,[38] Hindu philosophy at different times and in different states in modern India[39] and Islamic philosophy in Muslim countries[40] and more loosely when custodians of traditional belief systems control what can be thought and taught in traditional indigenous cultures.

In all of these cases, local science and philosophy was and has been made to answer to the dominant, institutionalised philosophy and worldview; and educational bodies were forced to accept such 'direction from above' as being in the interest of the nation, religion or culture. This cultural-political circumstance poses acute questions for the classroom science teacher: Should they foster independence of thought in their students or become functionaries of whatever the dominant ideological power might be? These are matters requiring a thoughtful and informed philosophy of education, unfortunately something mostly ignored in contemporary science teacher education where not only philosophy of education, but most foundational subjects have been progressively removed and replaced with training in pedagogical technique, classroom management skills and use of new technologies; the 'apprenticeship' model of teacher education allows little opportunity for 'reflection on principles' or for understanding the history and philosophy of the discipline being taught.[41]

50.6 Philosophy and Modern Science

Despite revolutions, paradigm changes, commercialisation and much else, modern science is continuous with the New Science of Galileo and Newton and prompts the same range of philosophical questions: Science and philosophy continue to go hand in hand.[42] Peter Bergmann expressed this point when he said that he learnt from Einstein that 'the theoretical physicist is … a philosopher in workingman's clothes' (Bergmann 1949, p. v, quoted in Shimony 1983, p. 209).[43] One commentator on the work of Niels Bohr remarked that 'For Bohr, the new theory [quantum theory] was not only a wonderful piece of physics; it was also a philosophical treasure chamber which contained, in a new form, just those thoughts he had dreamed about in his early youth' (Petersen 1985, p. 300). It is no accident that many of the major physicists of the nineteenth and twentieth centuries wrote books on philosophy and

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[38] See Beyerchen (1977) and Cornwell (2003).

[39] See Nanda (2003).

[40] On the tensions and accommodations between science and Islam, see Edis (2007) and Hoodbhoy (1991).

[41] On philosophy of education in science education, see Schulz (2009) and his contribution to this handbook; on the larger issue of educational foundations, see contributions to Tozer et al. (1990).

[42] Some useful studies on the philosophical dimension of science are Amsterdamski (1975), Buchdahl (1969), Burtt (1932), Dilworth (1996/2006), Smart (1968), Trusted (1991), and Wartofsky (1968).

[43] Paul Arthur Schilpp's anthology on Einstein is titled *Albert Einstein: Philosopher-Scientist* (Schilpp 1951).

the engaging overlaps between science and philosophy.[44] Many less well-known physicists also wrote such books teasing out relations between their scientific work and the ontology, epistemology and ethics that it presupposed and for which it had implications.[45] And not just physicists, many chemists and biologists have made contributions to this genre.[46]

This is not, of course, to say that all these good scientists wrote good philosophy or drew sound conclusions from their scientific work: Some did, others did not. Eighty years ago, Susan Stebbing wrote a classic critique of the hugely influential idealist philosophical conclusions drawn by the renowned British physicists James Jeans and Arthur Eddington (Stebbing 1937/1958). Mario Bunge has developed comparable arguments against the idealist and subjectivist conclusions drawn from quantum mechanics by David Bohm, Niels Bohr and many proponents of the Copenhagen school (Bunge 1967, 2012). The point is not that the major scientists drew common philosophical conclusions, it is rather that they all philosophised; they all reflected on their discipline and their activity, and they saw that such reflection bore upon the big and small questions of philosophy. This fact supports the contention that philosophy is inescapable in good science;[47] it should also suggest that philosophy is inescapable in good science education.

The Oxford philosopher, R. G. Collingwood in his landmark study *The Idea of Nature* wrote on the history of mutual interdependence of science and philosophy and commented that:

> The detailed study of natural fact is commonly called natural science, or for short simply science; the reflection on principles, whether those of natural science or of any other department of thought or action, is commonly called philosophy. … but the two things are so closely related that natural science cannot go on for long without philosophy beginning; and that philosophy reacts on the science out of which it has grown by giving it in future a new firmness and consistency arising out of the scientist's new consciousness of the principles on which he has been working. (Collingwood 1945, p. 2)

He goes on to write that:

> For this reason it cannot be well that natural science should be assigned exclusively to one class of persons called scientists and philosophy to another class called philosophers. A man

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[44] See, for instance, Bohm (1980), Bohr (1958), Boltzmann (1905/1974), Born (1968), Duhem (1906/1954), Eddington (1939), Heisenberg (1962), Jeans (1943/1981), Mach (1893/1960), Planck (1932), and von Helmholtz (1995).

[45] See, for instance, Bridgman (1950), Bunge (1998a, b), Campbell (1921/1952), Chandrasekhar (1987), Cushing (1998), Holton (1973), Margenau (1950), Rabi (1967), Rohrlich (1987), Weinberg (2001), and Shimony (1993).

[46] For instance, Bernal (1939), Birch (1990), Haldane (1928), Hull (1988), Mayr (1982), Monod (1971), Polanyi (1958), and Wilson (1998). One recent contribution to the genre is by Francis Collins, the geneticist and leader of the Human Genome Project (Collins 2007).

[47] There are countless books on the worldview of modern physics: see, for example, contributions to Cushing and McMullin (1989), especially Abner Shimony's contribution 'Search for a Worldview Which Can Accommodate Our Knowledge of Microphysics' (Shimony 1989). See also the contributions to the special issue of *Science & Education* dealing with Quantum Theory and Philosophy (vol. 12 nos. 5–6, 2003).

> who has never reflected on the principles of his work has not achieved a grown-up man's attitude towards it; a scientist who has never philosophized about his science can never be more than a second-hand, imitative, journeyman scientist. (Collingwood 1945, p. 2)

What Collingwood says about the requirement of 'reflecting upon principles' being necessary for the practice of good science can equally be said for the practice of good science teaching. Liberal education promotes just such deeper reflection and the quest to understand the meaning of basic concepts, laws or methodologies for any discipline (mathematics, history, economics, theology) being taught including science.[48]

50.7 Science and the 'Invisible World'

The world's major religions have had an ongoing engagement with science, investigating how their own ontological, epistemological, anthropological and ethical commitments – their worldviews – are to be reconciled with both scientific findings and scientific worldviews. Religion is the most publicly discussed and debated aspect of the science and worldview interaction and the one that most often occupies educators in their writing of national and provincial curricula, in their arguments about multicultural and indigenous science, in their debates about textbook selection and in their classroom teaching and interactions with students and parents. Because modern science emerged out of Christian Europe in the seventeenth century, the arguments and adjustments between Christianity and science – over Creation, Evolution, Providence, Miracles, Revelation, Authority – have been debated longest in this religious tradition, and hence it will be the focus of this chapter.[49] This section of the chapter will deal with just one of the many issues and debates that have arisen in the field: the putative existence and powers of spiritual agencies, spirits, ghosts, poltergeists and angels, inhabitants of what John Wesley, the founder of Methodism, called the 'Invisible World'.

50.7.1 Abrahamic Religions

Belief in a spirit-filled, invisible world is fundamental to the Judaeo-Christian-Islamic tradition. Jewish society simply took over the heavily populated world of demons that the Mesopotamian and Hellenic worlds also recognised with their ontology of beings intermediate between gods and men, these were the *daimones*. The Judaeo-Christian explanation of this realm of troublemakers and evil inducers

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[48] The Philosophy for Children movement has shown that this reflection and quest can begin in Elementary school (Lipman 1991; Matthews 1982; Sprod 2011).

[49] Among a veritable library of relevant books, see Barbour (1966), Brooke (1991), Haught (1995), Jaki (1978), Mascall (1956), and contributions to Lindberg and Numbers (1986).

was of course the expulsion from heaven of Satan and his fallen angels (Genesis 6:1–4). This was a more than satisfactory explanation of their existence, powers and inclinations. Jinn, or spirits and angels, were an integral part of the Judaic tradition, everyone in pre-Islamic Arabia believed in them; they lived in a world unseen to humans; they eat and drink and procreate; some are righteous while others are evil. Illness, unusual events, misfortunes, catastrophes and so on were attributed to this host of other-worldly ne'er-do-wells.

The New Testament and the early Christian Church which was a sect of Judaism simply carried on belief in the reality and powers of demons, or 'unclean spirits' as they are also called. These demons were responsible for false teaching (1 Timothy 4:1); they performed wonders (Apocalypse 16:14); they rule the kingdom of darkness (Ephesians 1:21, 3:10); and so on.

Of particular account in New Testament demonology is the widespread and frequent occurrence of possession of people by the devil or evil spirits. This continued a Judaic and Mesopotamian belief in diabolical possession, one that routinely attributed psychic illness (as now understood) to such a cause (Mathew 8: 16, 12:27; Mark 1:34; Luke 7:21, 11:19; Acts 19:13–16). The apostles exorcised evil spirits where they could, with the most graphic instance being the exorcism in the Gerasa cemetery where the demons fled the person and possessed the herd of swine that they then drove to their death in the Sea of Galilee. Converts such as Paul also had such powers and exercised them effectively such as when he drove the evil spirit from the girl from Philippi (Acts 16:16). Sometimes they were not successful, as with the boy now seen to be most probably an epileptic (Mathew 17:14–21; Mark 9:14–29; Luke 9:37–43).

John McKenzie, a Catholic commentator (from whom the foregoing textual references are taken), has written: 'The belief in heavenly beings thus runs through the entire Bible and exhibits consistency' (McKenzie 1966, p. 32). And further adds:

> But while the use of popular imagery should be understood to lie behind many details of the New Testament concept of demons, the Church has always taught the existence of personal evil spirits, insisting that they are malicious through their own will and not through their creation. (McKenzie 1966, p. 194)

The Protestant tradition held comparable views. Martin Luther wrote:

> Demons live everywhere, but are especially common in Germany. On a high mountain called Polterberg there is a pool full of them: they are held captive there by Satan. If a stone is thrown in a great storm arises and the whole countryside is overwhelmed. Many deaf persons and cripples were made so by the Devil's malice. Plagues, fevers and all sorts of other evils come from him. As for the demented, I believe it to be certain that all of them were afflicted by him. (In Mencken 1946/1930, p. 244)

John Wesley wrote in his *Journal* in 1768 that: 'The giving up of witchcraft is in effect the giving up the Bible'. He regarded witchcraft as 'one great proof of the invisible world'.

It is hardly surprising that half of all Americans tell pollsters that they believe in the Devil's existence, and 10 % claim to have communicated with him (Sagan 1997, p. 123). The extent of such belief has been more recently documented in the findings of the large-scale 2008 Pew Report on religious belief and practice in the USA.[50] This survey of 35,000 US adults, most of whom would have completed the high school science requirement, found that belief in some form of God was nearly unanimous (92 %) and that this God was not the remote, untouching God of eighteenth-century Deists, but a God who was actively engaged in the affairs of people and of processes in the world. Nearly eight in ten American adults (79 %) agree that miracles still occur today as in ancient times. Similar patterns exist with respect to beliefs about the existence of angels and demons. Nearly seven in ten Americans (68 %) believe that angels and demons are active in the world. Majorities of Jehovah's Witnesses (78 %), members of evangelical (61 %) and historically black (59 %) Protestant churches and Mormons (59 %) are *completely* convinced of the existence of angels and demons.

Belief in such a rich spirit-populated world 'invisible world' is a requirement for the world's 1.5 billion Muslims. Belief in angels is the second of Islam's six Articles of Faith. In Islam, Jinn are spirits made by Allah from smokeless fire; some Muslim scholars say that Jinn populated the earth 2,000 years before the creation of humans out of clay. The Islamic philosopher Seyyed Nasr writes:

> To rediscover the body as the abode of the Spirit…is to re-establish our link with the plants and animals, with the streams, mountains and the stars. It is to experience the Spirit in the physical dimension of our existence. (Nasr 1996, p. 262)

The whole constellation of traditional religious beliefs, especially those affirming an active ongoing engagement of God, angels and spirits with human affairs, requires that the world, including human beings, be constituted in certain ways; that the world has a certain ontology; and that the human beings are so constituted that it can know of and interact with these supernatural agencies. All of this amounts, in part, to a religious worldview, a view about how the world and human beings need to be constituted so as to enable, or ground, religious belief, experience and practice.

Henry Gill, a Catholic priest, philosopher and physics lecturer, gave succinct expression to the kind of worldview held by many of the above-mentioned religious believers:

> It will be useful to recall briefly the Catholic teaching as to the existence of spirits. The Scripture is full of references to both good and bad spirits. There are good and bad angels. Each of us has a Guardian Angel, whose presence, alas, we often forget. Angels, as the Catechism tells us, have been sent as messengers from God to man. Our Lady, at the Incarnation, St. Joseph before the flight into Egypt, both received messages. Our Lord Himself was tempted by Satan …. Finally, it is the certain teaching of the Church that the conditions which depend on whether the human being to whom it belonged has or has not lived according to the dictates of conscience and quitted this life in friendship or at enmity with God. (Gill 1944, pp. 127–128)

This statement implies and presupposes certain ontological, epistemological, anthropological and theological positions which rolled together constitute a statement of the traditional Roman Catholic worldview, a worldview that was 'at home' in

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[50] The survey was conducted between May and August 2007 and published in June 2008 in the Pew Report at www.pewreport.org.

Thomism and Scholasticism and is professed by a goodly number of the world's 1.2 billion Roman Catholics. The constituent domains of a worldview are meant to cohere. If one's ontology has angels and spirits existing with certain powers, then one's epistemology has to account for the possibility of this knowledge, and further it needs to indicate how the truth or falsity of claims about spirits can be ascertained. Is the epistemological ground for such claims Intuition? Authority? Religious Experience? or Revelation? It is rarely claimed that the ground is Science.

Despite being everywhere and being endowed with amazing powers and being variously credited with causing tsunamis, AIDS, schizophrenia, adultery, paedophilia and much else, such angels and spirits do not show up in laboratories or scientific texts; they have not gained a place in the scientific understanding of the natural, social or personal worlds. This gives rise to a certain disconnect. Such claims are then either discordant with, or orthogonal to, the worldview and conduct of science.

50.7.2 Traditional Societies

In traditional or indigenous cultures, these convictions about the 'invisible world' and interactions between this supernatural world and the everyday world are usually bolstered with animist beliefs where plants and natural objects are endowed with intelligences and spiritual attributes and where natural processes can be swayed by rituals, incantations, charms, potions, magic, sorcery and spells. In most such cultures, spirits are everywhere and have immense powers; they feature in traditional stories, legends and myths and underwrite a wide variety of social and medical practice.

Papua New Guinea is a representative case. In the early months of 2013, there had been a series of horrific sorcery-related gruesome murders committed. In January outside Mt Hagen, the capital of the Western Highlands, a 20-year-old mother was accused of sorcery, doused in petrol and burnt alive atop a pile of rubbish and car tyres. She supposedly had used her powers as a witch to kill a boy who had been admitted to hospital with chest pains. In March a highlands man ate his newborn son in order to bolster his sorcery powers. The same month in the Southern Highlands, six supposed witches were tortured with hot irons and one roasted to death. In April in Bougainville, two elderly women, accused of being witches and causing the death of a school teacher, were tortured for 3 days then beheaded in front of a large mob that included police officers. In just one Highland province, Simbu, there are 150 sorcery-inspired attacks per year.[51]

At the same time, the PNG government released a report on the AIDS epidemic in the country detailing the prevalence, and uselessness, of traditional treatments such as having sufferers sit atop huts inside of which is burnt 'special fires' in expectation that the rising smoke would carry off the evil spirits inhabiting the

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[51] See accounts and interviews in Elliot (2013).

person and causing the sickness. Such practices are widespread in the country where things are believed to happen not just for physical reasons because there can always be some non-natural trigger or cause for the happening; indeed the latter are so commonplace that to refer to them as 'non-natural' fails to understand the traditional worldview where 'white' and 'black' magic (*Sanguma*) are just part of how things are; *Sanguma* is everywhere and is recognised in the legal code. As one commentator remarked on these practices:

> In a remote world lacking scientific explanation, in which life could be brutish and short, it was natural that people sought not only a way to understand how their world worked, but also to find a way to take a measure of control over it. (Callick 2013, p. 11)

The reality and efficacy of sorcery is recognised in the 1971 *Sorcery Act*. A 1977 PNG Law Commission study on 'Sorcery in PNG' concluded:

> We have written some general ideas about sorcery we know from our own experience as Papua New Guineans. In order to get a balanced view of sorcery we would like to say that sorcery is very much a matter of the innermost belief of the people. Fear of, or the practice of sorcery or various occults is a world-wide phenomenon. Sorcery or black magic exists in Europe, in Asia, in Africa and in North and South America as well as the Pacific.
>
> Major world religions claim the reality of forces or personalities greater than the human and animal powers. Whether these powers or personalities can be shown to exist is often quite irrelevant to the belief. From these beliefs many practices and procedures follow. (Narokobi 1977, p. 19)

The 2013 revision of the legal code is moving to deny the reality of such powers and make supposed *Sanguma* bashings, torture and killings criminal offences.

A long-time PNG Catholic priest, Philip Gibbs, recognised the incompatibility of Enlightenment-informed scientific worldviews and biblical worldviews when he described PNG culture as having a:

> Pre-Enlightenment, or Biblical, worldview … They don't believe in coincidence or accidents. When something bad happens, they don't ask what did it but who did it. (Elliot 2013, p. 18)

The situation with PNG traditional society is repeated in sometimes more and other times less extreme forms in most traditional societies and other societies, where the spirit world looms large and where centuries, if not thousands of years, of tradition, folklore and superstition are embedded.

Ancient rock art of the Australian aboriginal Worrorra people has recently been re-discovered in the spectacular Kimberley country in north-west Australia. The recurrent image is of Wandjinas, the supreme spirit who created the country during the Dreamtime. The Worrorra belief is:

> The Wandjinas created the animals and the baby spirits that live in the rock pools or sacred Ungud places throughout the Kimberley, and they continue to control everything that happens on the land, sea and sky. (http://wandjinatours.com.au/)

It is routine in most Southeast Asian countries for residential and other buildings to have 'spirit houses' prominently placed so that spirits disturbed in the construction have a new home; a home where food and offerings are left so the annoyed spirits do not do mischief. Some such beliefs and 'the practices and procedures' based on them are benign, while others are dramatically less so.

'Smoking' ceremonies where Australian aboriginal people gather and burn special leaves so the spirit of a deceased can be released and be carried upwards with the smoke to 'heaven' are a benign example.[52] The case of a New Zealand Maori couple who in November 2007 gouged out the eyes of their 14-year-old daughter in order to allow the escape of a bad spirit who supposedly possessed the girl is a less benign example. This 'exorcism' was witnessed by 40 relatives.[53] Of course these beliefs and practices are not just those of 'traditional' societies: Not long after the Maori episode, the Vatican's official exorcist, Father Gabriele Amorth, who has conducted 70,000 exorcisms, claimed that many paedophilia cases were the direct work of devils who possessed or otherwise influenced the offending priests (Amorth 2010).

When politicians, doctors, nurses and educated community members deny the efficacy or existence of 'bad' spirits or devils, they are involved in proto-science. The basic claim is that 'there is no evidence' for such possession and that the evidence (paedophilia or children dying) can be accounted for by other natural causes. This basic claim moves discussion into the field of science and evidence appraisal. But once that move is made, then why not extend the examination to the efficacy or existence of 'good' spirits and angels?

50.7.3 Feng Shui

Non-scientific, and in some cases anti-scientific, worldviews are widespread in advanced economies and cultures where commitment to astrology, parapsychology, levitation, clairvoyance, mediums, extrasensory perception, the paranormal, telepathy, astral travel, Thiaoouba consciousness and so on are common.[54]

One entrenched practice and theory that does not attract the attention it warrants is feng shui (Rossbach 1984). Millions of Chinese believe in its principles, and increasingly it is being adopted outside of the Chinese community. Feng shui advising is a thriving business with thousands of consultants, and law courts determining whether correct or incorrect feng shui advice was given in cases where poor business returns or illness follows occupancy of feng shui-certified commercial and residential buildings.

Feng shui, or Chinese geomancy, derives from an ancient Chinese system of rules, concepts and principles that endeavours to explain the impact on people's lives of the layout and design of their business and home. Its origins lay in the 3,000-year-old writing, *I Ching*, of the ancient sage Fu His who had the inspiration that the diverse fundamental forces of the universe were mirrored in the orderly markings on the shell of the tortoise which when arranged in threes gave eight

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[52] There is a parallel use of incense in the Roman Catholic burial liturgy.

[53] *Sydney Morning Herald* November 27, 2007

[54] On this phenomena, see Dawkins (1998), Sagan (1996), Shermer (1997) and the classic study by W. E. H. Lecky (1914). Hundreds of thousands of websites are devoted to these 'alternative' science practices and 'theories'.

trigrams corresponding to Heaven, Earth, Fire, Water, Mountain, Lake, Wind and Thunder (Spear 1995, Chap. 5).[55] Unlike the case of chaotic and inconsistent good or bad spirits, feng shui purports to describe regular, lawful natural processes in just the same way that science does. But over and above the mundane energy of science, there is another universal life force called Chi or Mana. One feng shui exponent explains that:

> Chi is the vital force that breathes life into the animals and vegetation, inflates the earth to form mountains, and carries water through the earth's ducts … Without chi, trees will not blossom, rivers will not flow, man will not be. (Birdsall 1995, p. 37)

But chi is a peculiar kind of vital energy as:

> Doors are seen as the entrance of chi for any place. A building, house or room takes in its chi through the doors and, to a lesser extent, the windows. If the doors are too small then not enough chi will get into a place too many doors down a corridor may affect and confuse the flow of chi. (Birdsall 1995, p. 129)

And being more precise:

> One of the classic rules of feng shui…is that if you have a toilet in the wealth corner of your home or business, then you are likely to have financial or abundance troubles. (Birdsall 1995, p. 117)

However there is a correction for such faulty construction:

> Place a crystal in the window of the bathroom to draw in the universal chi. (Birdsall 1995, p. 118)[56]

And so on for 200 pages of this popular book. But the author moves from relatively trivial and harmless nostrums to something more arresting:

> Science can no longer dismiss the concept of our energetic body existing outside our physical bodies, as the former can now be photographed and analysed by Kirlian photographs. Often disease can be seen in the auric body before it shows in the physical body. (Birdsall 1995, p. 38)

But these high-energy photographic effects have everything to do with effects of changes in proximal humidity around bodies and nothing to do with supposed auras; as water vapour is progressively removed from around a hand or head, the aura image disappears. Basing medical diagnosis and treatments on such foolery can do damage, quite apart from wasting people's money.

With its commitment to ontological, epistemological and axiological principles that guide behaviour, feng shui counts as a worldview, one that is held by millions of people. As one advocate writes: 'More than just the practice of geomancy, placement, or spatial arrangement, feng shui is also a philosophy or a way of seeing the world' (Spear 1995, p. 15). And where it is not a self-contained worldview, it is a component that its believers' wider worldviews need to accommodate.

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[55] There are over 100 English translations of the basic text, *I Ching*.

[56] Another advocate who addresses this problem does admit that 'no feng shui cure can be as powerful as a properly placed, flawless diamond to activate chi in an environment' (Spear 1995, p. 131).

Following feng shui ‘principles’ often does no harm. It is like the fabled Notre Dame football coach who said that God most answered the team’s prayers when ‘the forwards were big and the backs were fast’; or knowing that ‘with an uncle’s blessing and one dollar, you can ride the subway’. So if you build in such a way that your living quarters receive natural sunlight, then it is just a bonus that the room also falls on a good chi line and has auspicious bagua. Ditto if your bedroom has a window that does after all let in fresh air. But feng shui belief can do harm, and it is a distraction: Sometimes illness is caused by an infection, and poor profit results are the outcome of bad business decisions. In such cases rearranging the furniture or putting in an extra door, mirror or even a diamond will make no difference to the malady.

If teachers have some training in history and philosophy of science, the philosophical implications of feng shui can be drawn out. There are a host of questions and tasks that can usefully occupy students:

What are the claims of feng shui and are they scientifically testable?
Do other theories have the same implications and thus are they equally supported by whatever experimental evidence might support feng shui?
Where there are two, or more, such theories consistent with the empirical evidence [people in sunny houses feel well and suffer less colds] can any crucial experiment be devised to evaluate the theories?
Are feng shui predictions and theory elaboration all ad hoc? And what is wrong with ad hoc adjustments in theory?
Is feng shui a progressive research programme making novel claims or a reactive or degenerating one which only embraces claims made on other grounds?
How can the cultural, social and economic pros and cons of feng shui be explicated and appraised?

And this drawing out can be done by social science and science teachers working together.

For science teachers in cultures where feng shui is part of the social fabric, such questions can be used as a way into better understanding of the nature and methods of science, including the question of the function of naturalism in science and in culture. And orthodox religious belief, traditional cultural beliefs, astrology, psychokinesis, aura therapy, psychoanalysis and anything else can be substituted for feng shui in the foregoing questions. Each question draws on routine discussion in philosophy of science, and so each question can be the occasion for elaboration and learning of the latter.

50.7.4 Education and the ‘Invisible World’

Thus far no such traditional, or other, spirits have been identified by science as having any causal interaction with the world. Yet they are very much a central part of the worldviews of several billion people. The educational question is what to do about such beliefs? Should nothing be done and the cultural status quo retained unaltered? Should students be encouraged to believe just in good spirits and not in bad ones?[57] And if they are to believe in good spirits, should they believe for ontological reasons (there actually are such things) or for instrumental reasons (such belief is harmless and part of the cultural or religious tradition)? Or not believe in spirits at all?

The last was the choice of Joseph Priestley, the famed eighteenth-century English scientist, historian, philosopher, theologian and Dissenting Church minister[58]:

> The notion of madness being occasioned by evil spirits disordering the minds of men, though it was the belief of heathens, of the Jews in our Savior's time, and of the apostles themselves, is highly improbable; since the facts may be accounted for in a much more natural way. (Rutt 1817–1832/1972, vol. 7, p. 309)

For Priestley, Jesus was simply mistaken when he attributed the cure of madness to driving out evil spirits because subsequent science and philosophy had shown there were no such things to be driven out.[59]

Whether the Abrahamic religious traditions or 'indigenous' traditions can abandon belief in all, most or just some of 'the invisible world' is an engaging theological and cultural question, but the grounds for such discussion can usefully be prepared by discussions in philosophy of science about what constitutes 'hard-core' commitments in a research programme and how these are separated from 'protective belt' commitments – to use the terminology of Imre Lakatos (1970). Philosophers of science have for long dealt with the questions of what are the 'core' commitments of a research programme and what are 'optional' commitments, and familiarity with these discussions and analyses can inform comparable discussion about religion and important cultural beliefs.

50.8 Multiculturalism and Science Education

Examples of spirit-laden cultures and traditions have been given above. It was pointed out that such belief constellations were either discordant with or orthogonal to science, with the latter depending on whether spiritual, or supernatural, agencies had engagement with the world. In these latter cases, the relationship is not orthogonal; once it is claimed that the 'invisible world', or supernatural agencies, connect to the world and have worldly impacts, then they enter the domain or 'magestria' of

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[57] In March 2013 Indonesia's criminal law statutes were being rewritten so as to make the practice of black magic (where people are harmed by sorcery) illegal but keep white magic legal. This raises not just ethical questions but engaging philosophical ones as well. Does a 'guilty' verdict acknowledge that such powers of mind over matter were exercised?

[58] The basic texts for Priestley's life, writings and achievements are Schofield's (1997, 2004). See also de Berg (2011), Matthews (2009c).

[59] In passing it is worth noting that every account of Priestley's life shows that a deeply 'spiritual' life is possible without any belief in spirits.

science. It was also suggested that students can be encouraged to engage in a number of routine philosophical questions about such belief systems. Such questions and pedagogy raise important matters about the purposes of science education and the distinction between *understanding* science and *believing* science. Some maintain that science education should leave cultural beliefs untouched, that students should simply leave their culture's worldview (ontology, epistemology, metaphysics, authority structure, politics and religion) at the classroom door, then enter inside to learn the instrumentally understood content of science, then go back outside and become again full-believing participants in their culture. This is close to advocating an anthropological approach to learning science. Just as anthropologists can be expected to learn *about* the beliefs and practices of different societies without any expectation that they adopt or come to believe them, some say that students can learn science in the same way, a sort of 'spectator' learning where one learns but does not believe.

Glen Aikenhead, in a much cited paper, has advocated such a strategy calling it 'border crossing' (Aikenhead 1996, 2000). Just as tourists when they cross borders do not lose their cultural identity even though they temporarily adopt foreign customs about driving, eating, dressing and language, so also science students should not lose their cultural identity (as a traditional Catholic, a fundamentalist Christian, an Intelligent Designer, a PNG highlander, a feng shui enthusiast and so on) just because the science laboratory has no place for their own rich beliefs. This 'border-crossing' option is a form of pedagogical NOMA; it is a profoundly anti-Enlightenment view.

Early modern and Enlightenment philosophers thought much would be gained if the method of the New Science might be applied to the seemingly intractable social, political, religious, philosophical and cultural problems of the times. During the period of Galileo's most productive work, the terrible 30 Years' War (1618–1648) raged all over Europe – in German states, France, Italy, Spain, Portugal and the Netherlands – and was also fought out in the Indies and in South America. It is widely accepted that between 15 % and 20 % of the German population, Catholic and Protestant alike, were killed. Along with ferocious religious wars witch crazes also engulfed Europe with the worst excesses occurring in France, Switzerland, Germany and Scotland. In the Swiss canton of Vaud, in the 90 years between 1591 and 1680, 3,371 women were tried for witchcraft and all were executed (Koenigsberger 1987, p. 136). The Salem witch trials took place in Massachusetts in 1692, 5 years after publication of Newton's *Principia*. As late as 1773, nearly 100 years after publication of Newton's *Principia*, the Presbyterian Church of Scotland reaffirmed its belief in witchcraft; but Catholic Spain has the distinction of being the last European country to burn a witch at the stake, this being in the early nineteenth century. And the lamentable practice still goes on in Papua New Guinea, Africa and doubtless many other traditional societies untouched by science and the Enlightenment.

Newton believed that there would be beneficial flow-on effects if the methods of the New Science were applied to other fields. As he stated it: 'If natural philosophy in all its Parts, by pursuing this Method, shall at length be perfected, the Bounds of

Moral Philosophy will be also enlarged' (Newton 1730/1979, p. 405). David Hume echoed this expectation with the subtitle of his famous *Treatise of Human Nature* which reads *Being an Attempt to Introduce the Experimental Method of Reasoning into Moral Subjects* (Hume 1739/1888).

The contrast between the aspirations of the Enlightenment philosophers and contemporary 'border-crossing' science educators is profound and speaks to a major divergence in their appreciation of science. This indeed is the case, with Glen Aikenhead maintaining that 'the social studies of science' reveal science as:

> mechanistic, materialist, reductionist, empirical, rational, decontextualized, mathematically idealized, communal, ideological, masculine, elitist, competitive, exploitive, impersonal, and violent. (Aikenhead 1997, p. 220)

This claim is as puzzling as it is disturbing. Is the claim meant to describe the work of Galileo? Newton? Huygens? Darwin? Mendel? Faraday? Mach? Thompson? Lorentz? Maxwell? Rutherford? Planck? Einstein? Bohr? Curie? Does it describe the work of Edward Jenner in developing smallpox vaccine? Or the achievements of Jonas Salk and Albert Sabin in developing polio vaccine? We are not told whose science warrants the description. It is clearly a composite or collage that requires unpicking, but this is not done – the good, the bad and the ugly are all lumped together. Unfortunately there are numerous cases of corrupt science – Nazi and Stalinist science being the best-known examples – but these do not warrant generalisations, they warrant correction. From Aikenhead's undifferentiated description, it is doubtful whether science should even be in the curriculum; it certainly should be rated X, with even border crossing being dangerous for minors. Other prominent and influential science educators share Aikenhead's unfavourable estimation of science. Consider, for instance, the demand that teachers need to:

> deprivilege science in education and to free our children from the 'regime of truth' that prevents them from learning to apply the current cornucopia of simultaneous but different forms of human knowledge with the aim to solve the problems they encounter today and tomorrow. (Van Eijck and Roth 2007, p. 944)

Or the claims made in a contribution to a current major science education handbook that:

> … one of the first places where critical inquirers might look for oppression is positivist (or modernist) science … modernist science is committed to expansionism or growth … modernist science is committed to the production of profit and measurement …modernist science is committed to the preservation of bureaucratic structures. (Steinberg and Kincheloe 2012, p. 1487)

> Science is a force of domination not because of its intrinsic truthfulness, but because of the social authority (power) that it brings with it. (Steinberg and Kincheloe 2012, p. 1488)

> Modernism refers to a way of understanding the world produced by Enlightenment thinkers and employing a scientific methodology and the concept of rationality Drawing on dualism, scientists asserted that the laws of physical and social systems could be uncovered objectively; the systems operated apart from human perception, with no connection to the act of perceiving …. This separation of mind and matter had profound and unfortunate consequences. (Steinberg and Kincheloe 2012, pp. 1490, 1491)

Such appraisals demonstrate the need for science educators to be careful and considered in their reading and studies of history and philosophy of science; clearly a little knowledge is a dangerous thing. The above accounts, apart from being confused and contradictory, cannot be sustained. Taking the subject *out* of the picture and relying on measuring instruments (rulers, scales, thermometers, barometers, clocks) instead of subjective appraisals of length, weight, temperature, pressure and duration; utilising mathematics; introducing idealisations and abstractions; valuing objective evidence; and being public, communal, publishing, criticising and debating are all the things that enabled the Scientific Revolution to occur in seventeenth-century Europe and progress to its current international status. And of course Copernicus and Galileo had no social authority enforcing their heliocentricism, on the contrary; while Lysenko had all the oppressive authority of Stalin behind his non-Mendelian genetics and it counted scientifically, and ultimately, for nothing. All of this is missing in the accounts of science given by the above science educators.

50.9 Philosophical Systems and Religious Belief

The juxtaposition of scientific and religious worldviews brings into focus a number of enduring philosophical, religious and cultural issues, among which are at least the following:

1. Do religions make metaphysical claims? Are there preferred philosophical systems for the expression of such claims? Are particular religions tied to such systems?
2. Is there a need for religious claims to be made intelligible and testable? Or is Faith deeply personal, experiential and indefinable? Is Faith apart from and beyond Reason?
3. Should philosophical systems be judged by their theological adequacy or compatibility?
4. Should religious establishments (churches, priests, ministers, imams, ulama) have the authority to proscribe philosophical systems or metaphysics to their co-religionists? Should they be able to proscribe to others outside their religion when their religion exercises or influences state power?

These issues were argued within the Christian churches; they were debated in the Enlightenment and are still debated.[60] For example, Claude Tresmontant in his *Christian Metaphysics* argues that:

> The thesis which I submit to the critical examination of the reader is that there is *one* Christian philosophy and one only. I maintain, in other words, that Christianity calls for

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[60] For representative literature on this topic of ‘Christian Philosophy’, see Mascall (1966, 1971), Plantinga (2000, 2011), Tresmontant (1965), and Trethowan (1954). The suitability of Thomism as a vehicle for the interpretation of Christian doctrine is discussed in McInerny (1966). The same debates and literatures can be found in Islamic, Judaic, Hindu and other traditions.

> a metaphysical structure which is not any structure, that Christianity is an original metaphysic. … [it is] a body of very precise and very well-defined theses which are properly metaphysical …. (Tresmontant 1965, pp. 19–20)

The Catholic priest, philosopher and historian of philosophy, Fredrick Copleston wrote of his celebrated 1949 debate with A. J. Ayer that:

> After all, my defence of metaphysics was largely prompted and certainly strengthened by what I believed to be the religious relevance of metaphysical philosophy. (Copleston 1991, p. 63)

One such common metaphysical position, vitalism, is clearly stated by another Catholic priest and philosopher:

> That there is a fundamental difference between living and non-living matter is obvious. Catholic philosophers hold that an organized or living substance is distinguished from inanimate matter in that the former is informed by a 'vital principle' which confers on it the characteristics we associate with life. (Gill 1943, p. 73)

Such a position might be labelled 'privileged' in as much as the metaphysics comes from outside of science, not from within. Privilege for such metaphysical positions is usually derived from Revelation, Theology, Religious Experience, Philosophy, Intuition or Politics. Such privileged metaphysical views can be found enunciated by advocates of Judaic, Islamic, Hindu, Buddhist and a host of other religions, as well as advocates of the maintenance of indigenous belief systems and worldviews. These traditions would formulate the above four fundamental issues in their own terms. For instance, if 'Marxism-Leninism' is substituted for 'religion' and the 'Central Committee' substituted for 'religious authorities', then the above list of issues is applicable to the situation that pertained in the Soviet Union and its satellites and still pertains in China. No authoritarian state, since the Athens that put Socrates to death, has welcomed open and free philosophical study and debate.[61]

50.9.1 Compatibility of Science and Religion

When considering the compatibility of science and religion, we need to distinguish a number of sometimes conflated issues[62]:

First, whether religious claims and understandings have to be adjusted to fit proven scientific facts and theories. There really is no longer any serious debate on this issue; sensible believers and informed theologians acknowledge that religious

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[61] Anthony Kenny, the British philosopher and former Catholic priest, depressingly relates in his autobiography how as a doctoral student at Rome's Gregorian University he needed his supervisor's permission to read David Hume's *On Religion* and that his degree would not be awarded unless he affirmed an anti-Modernist oath (Kenny 1985, p. 146).

[62] Different taxonomies or ways of classifying science/religion relationships are developed in Barbour (1990), Haught (1995) and Polkinghorne (1986). These, and others, are discussed in Mancy et al. (in press).

claims need to be modified or given a nonliteral interpretation to fit with proven or even highly probable science. Joseph Priestley, the eighteenth-century Enlightened believer, told the story of ‘a good old woman, who, on being asked whether she believed the literal truth of *Jonah* being swallowed by the whale, replied, yes, and added, that if the Scriptures had said that *Jonah* swallowed the whale, she would have believed it too’. Priestley thought that such convictions simply indicated that the term ‘belief’ was being misused in the context: ‘How a man can be said to *believe* what is, in the nature of things, *impossible*, on any authority, I cannot conceive (Rutt 1817–1732/1972, vol.6, p. 33). All serious thinkers on the topic, since St Augustine, agree with Priestley.[63]

Second, whether religious believers can be scientists. Again, at one level, there is no debate on this matter. As a simple matter of psychological fact, there have been and are countless believers of all religious stripes who are scientists.[64] But this sense of compatibility is of some but not determinate philosophical interest. The arguments and evidences put forward by these numerous eminent and believing scientists are relevant to the question of rational compatibility but not just the fact that there are such believers. Undoubtedly some scientists are astrologers, others channel spirits, some might think they are Napoleon reincarnated, some are racist and others are sexist and so on for a whole spectrum of beliefs that, as a matter of fact, have been held by scientists. No one doubts that science, as a matter of psychological fact, is compatible with any number of belief systems – recall that the Nobel laureates Philipp Lenard and Johannes Stark were both Nazi ideologues. Scientists are humans, and humans notoriously can believe all sorts of crazy things at the same time; but such psychological compatibility has no bearing on the rationality or reasonableness of their beliefs or the philosophical compatibility between science and belief systems. The latter is a logical or normative matter. The philosophically interesting question is whether a scientist can be a *rational* religious believer (or astrologer, diviner, reincarnationer, racist, sexist, Nazi, etc.).

Third, whether religion is compatible with the metaphysics and worldview of science. Where there is incompatibility between scientific and religious

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[63] There has been debate about just what degree of proof a factual scientific claim needs to have before it triggers a revision in a competing factual religious claim – Augustine thought revision was needed only in the face of absolutely proven ‘scientific’ claims. The details of this debate do not bear on the present argument; for the arguments and the debate’s literature, see McMullin (2005).

[64] John Polkinghorne, an Anglican priest, could be picked out as an exemplar of a research physicist and believer (Polkinghorne 1986, 1988, 1991, 1996). Many such individuals can be found contributing to journals such as *Zygon: Journal of Religion & Science*. For just one compilation of contemporary Christian scientists, see Mott (1991). There are comparable compilations of Hindu, Islamic, Mormon and Judaic scientists. There may even be compilations of Scientologist scientists and Christian Science scientists. These lists are relevant to the question of the psychological compatibility between scientific and religious beliefs, but not their philosophical or rational compatibility.

metaphysics and worldviews – as in the case of atomism and traditional Roman Catholic doctrine developed above – the options usually taken to reconcile the differences are to claim that:

1. Science has no metaphysics; it deals just with appearances and makes no claims about reality. This is the option made famous by the Catholic positivist Pierre Duhem.[65] It is the claim made by many fundamentalists who say, specifically of evolution, that 'it is just a theory'.
2. The metaphysics of science is false; at least any such purported metaphysics that is inconsistent with religious beliefs. This is the option advocated by the Scholastic tradition discussed above; by Claude Tresmontant and Seyyed Nasr who are quoted above; and by philosophical theologians such as Alvin Plantinga (2011), E. L. Mascall (1956) and numerous others.
3. There can be parallel, equally valid, metaphysics. This is an old option given recent prominence by Stephen Gould in his NOMA formulation (Gould 1999).

Gould's much-repeated claim was that:

> The magisterium of science covers the empirical realm: what the Universe is made of (fact) and why does it work in this way (theory). The magisterium of religion extends over questions of ultimate meaning and moral value. These two magisteria do not overlap, nor do they encompass all inquiry (consider, for example, the magisterium of art and the meaning of beauty). (Gould 1999, p. 6)

The problem for NOMA is that, apart from classical Deists for whom God stays remote in His heaven and has no dealings with His creation, the core conviction of religious traditions is that the two realms overlap: that the supernatural has engagement with the natural; that God engages with His Creation; that certain texts (Torah, Bible, Koran, Book of Mormon, Sikh scriptures) are inspired, if not divinely written; miracles occur; prayers are answered and so on. However as soon as claims are made for supernatural engagement with the natural world and processes, then they come within the magestria of science: The cause might be of another world, but the effect is of this world. Such causal claims need not and should not be ignored by science; science can test claims about miracles, supernatural interventions and even Divine authorship, just as it can test claims about putative paranormal and psychic occurrences.[66]

50.9.2 *Scientific Study of Scripture*

Because so much hinges upon it, the very possibility of a 'scientific' or scholarly investigation of sacred texts or Scriptures has always been contentious in all

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[65] See extensive discussion and bibliography in Martin (1991).

[66] The anti-NOMA view that science can test supernatural claims is convincingly argued by many, including Boudry et al. (2012), Fishman (2009), Slezak (2012), and Stenger (1990, 2007).

'scripture-based' religious traditions. One historian of the origins of modern biblical scholarship writes that:

> Thus it is not surprising as may be thought that we can turn firstly to two *scientists* (this shows the importance of the Copernican revolution for the beginning of the historical-critical method) who are not usually thought of in this connection at all: Johannes Kepler and Galileo Galilei. (Andrew 1971, p. 95)

Galileo's 1615 *Letter to the Grand Duchess Christina* was perhaps the first clear statement in the Christian tradition of the view that Revelation should be investigated in the same way that other cultural artefacts and natural objects were investigated, namely, scientifically (Galileo 1615/1957). Galileo, in order to defend Copernicanism against those bringing scriptural objections to a rotating Earth, argued that Scripture had to be interpreted by Reason, and where there was conflict between Scripture and claims established conclusively by Reason, then Scripture had to be reinterpreted accordingly. Galileo was appealing to a well-established interpretative tradition in the Catholic Church going back at least to St Augustine, a tradition that acknowledged that not everything in Scripture was to be read literally as many things simply could not have occurred: Moses authoring the entire Pentateuch including the story of his own death; Jonah surviving in the whale; Methuselah living for 969 years; a flood that covered the whole earth, but of which other nations knew nothing; iron axe heads floating on rivers; numerous people rising from the dead; and so on. These stories had to be read metaphorically or poetically. But the Church was the authority that decreed what text was literal and what was poetic.

Baruch Spinoza's 1670 *Tractatus Theologico-Politicus* (Spinoza 1670/1989) is widely regarded as the first comprehensive attempt to state the exegetical principles of modern, secular, historical study of the Judaeo-Christian scriptures; the study of biblical history removed from theological dogma. He wrote in Chap. 7: 'the method of interpreting Scripture is no different from the method of interpreting Nature, and is in fact in complete accord with it' (*TTP* 3.98). This meant first, attention to the text only and not to tradition; second, adopting the primacy of 'Natural Reason' in interpretation of scriptural text. As a consequence in an ecumenical display, Calvinist ministers and Jewish rabbis combined to drive Spinoza from Amsterdam.[67] Some Enlightenment figures, Edward Gibbon and John Toland, for instance, thought scripture so imperfect that the advance of human reason simply dissolved revelation. Toland claimed that 'there is nothing in the Gospel contrary to reason' and then crucially added 'or above it' (Hyland et al. 2003, p. 60). The postscript ruled out recourse to affirmations of unanchored faith.

The addition was crucial because Kepler, Galileo and others admitted that scripture asserted things that were 'beyond human understanding' and so not contrary to human understanding; in the latter cases, scripture had to be reinterpreted, and in the former, there was no need to do so. This meant a cleavage in the reach of the Galilean method. For Toland and most Enlightenment thinkers, the 'beyond human reason'

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[67] On Spinoza and the adoption of 'scientific method' in biblical studies, see Bagley (1998) and contributions to Force and Popkin (1994).

category was not countenanced; science was the arbiter separating literal from poetic in biblical texts.

In the mid-nineteenth century at the time of Pius IX, the German schools of Hermeneutics and higher Biblical criticism represented the more radical wing of Enlightenment views about the scholarly study and interpretation of Revelation. The Pope was particularly outraged by Ernest Renan's just published *Vie de Jésus* (Renan 1863/1935)[68] which he said ought to have been suppressed by the French government; it was so suppressed, along with most of the Enlightenment canon, in the Papal States and in other Catholic countries where the Church yielded political and judicial influence.

Salman Rushdie, the Muslim apostate who was condemned to death by the Iranian spiritual leader Ayatollah Khomeini, has recently written that:

> What is needed is a move beyond tradition – nothing less than a reform movement to bring the core concepts of Islam into the modern age. … If, however the Koran were seen as a historical document, then it would be legitimate to reinterpret it to suit the new conditions of successive new ages.

In saying this, Rushdie is claiming no more than what, informed by modern science, European Enlightenment figures of the eighteenth century asserted. One can only believe that the ensuing working out of this claim, to see Scripture as a historical text, will be the same in Islam as it has been in Christianity and in Judaism where the claim has been grappled with for four centuries. For some the Divine content of Revelation will evaporate, for others what will be revealed will be what Reason permits to be revealed, and for others such as those holding to some version of the 'Inerrancy of Scripture' doctrine, there will be some uneasy accommodation between Reason and Revelation.

50.10 Science and Naturalism

The conduct of science presupposes at least methodological naturalism (MN). This is the view that, when doing science, whatever occurs in the world is to be explained by natural mechanisms and entities and that these entities and mechanisms are the ones either revealed by science or in principle discoverable by science. This methodological presupposition does not rule out miracles or Divine interventions or other non-scientific causes; it just means that such processes cannot be appealed to while seeking scientific explanations. There has been historically a transition from more open or mixed methodology to having MN function as a defining principle of scientific investigation. As Robert Pennock states the matter:

> … science has completely abandoned appeal to the supernatural. In large part this is simply the result of consistent failure of a wide array of specific 'supernatural theories' in competition with specific natural alternatives. (Pennock 1999, p. 282)

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[68] Other contributors to this 'higher criticism' or scientific study of texts were Friedrich Schleiermacher (1763–1834), F. C. Bauer (1792–1860) and David Strauss (1808–1874).

A stricter version of naturalism is ontological naturalism (ON), which sometimes is called metaphysical naturalism. This is the view that there is a scientific explanation for all events, that supernatural explanations (e.g. Divine interventions, miracles) simply do not occur. Many see ON as pure dogmatism, and it can be if it is held in advance as a philosophical principle. But it can be held on less dogmatic two-step grounds:

(i) Thus far no credible evidence has been advanced for the existence of any putative non-natural entity, or entity not within the scientific realm.

Many of course reject (i), and that is a whole separate argument. But some accept (i) and nevertheless say that ON does not follow from it or only follows dogmatically, as no one knows that evidence might turn up. But the nondogmatic holder of ON can add a second step to their argument:

(ii) Do not believe things for which there is no evidence.

If (ii) is granted, then ON does indeed follow. Then the dogmatism claim moves back to belief in (ii) rather than belief in ON. But belief in (ii) need not be dogmatic; it can be the 'default' position and its opposite, namely, the holding of beliefs for which there is no evidence, is dogmatic. This was in essence Bertrand Russell's 'teapot' argument.

> I ought to call myself an agnostic; but, for all practical purposes, I am an atheist. I do not think the existence of the Christian God any more probable than the existence of the Gods of Olympus or Valhalla. To take another illustration: nobody can prove that there is not between the Earth and Mars a china teapot revolving in an elliptical orbit, but nobody thinks this sufficiently likely to be taken into account in practice. I think the Christian God just as unlikely. (Russell 1958)

Both science-informed methodological and ontological naturalists admit the existence of whatever kinds of entities (e.g. atoms, fields, forces, quarks) science reveals as having regular causal relations with the rest of nature. But ontological naturalists do not admit the existence of spiritual or Divine entities or any kind of entity that does not enter into scientifically demonstrated lawful and causal relations with nature.[69] Traditional religious believers must reject ontological naturalism, but of course religious scientists routinely adopt methodological naturalism in the laboratory; to do otherwise would put them outside of the scientific enterprise.[70]

Materialists are a subspecies of ontological naturalists, but they are less relaxed about what can exist. Basic or 'old-fashioned' materialists grant existence only to

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[69] Although often confused, there is a difference between realism and naturalism (including Materialism). Realism simply asserts that there is a world independent of human thought. Such an independent world might include spirits, minds, universals, mathematical objects, forms or any other independent existent. Realism neither rules in or rules out any particular kind of putatively existing being. A theological realist about angels believes that angels exist, not that the word 'angel' is shorthand for 'makes people behave' or 'strengthens our cultural bonds'. Naturalism is a subspecies of realism, it asserts that the only existing things are the things that science postulates and incorporates into successful and mature theories; materialism in turn is a subspecies of naturalism.

[70] On naturalism see Martin Mahner's contribution to this handbook. See also Fishman and Boudry (2013), De Caro and Macarthur (2008), Devitt (1998), French et al. (1995), Mahner (2012), Nagel (1956), and Wagner and Warner (1993)

material, physical, ‘three-dimensional’ objects, the kind of things that can be tripped over. They reject the postulation of nonmaterial scientific entities, believing that such postulation is a failure of scientific nerve and it is the slippery slope to idealism.[71] This is clearly as much an a priori metaphysical position as it is a deduction from scientific practice. Emergent materialism is a more sophisticated version where the world is seen as material but stratified. The properties of material aggregations are greater than, and different from, the properties of the building blocks. So cells have different kinds of properties than molecules, brains have different properties than neurons, societies have different properties than individuals and so on. For emergent materialists, the world is changing and evolving, and new properties emerge from more complex material formations.[72]

50.11 Worldviews and Philosophy in Science Classrooms

To state the obvious: It is important for teachers to recognise how science lessons engage with the religious beliefs and worldviews of students. Much has been written on this topic.[73] It needs to be remembered that the more profound philosophical dimensions of science can be approached in classrooms and curricula through small steps; there is no need to go in at the deep end. Any science textbook will contain terms such as ‘observation’, ‘evidence’, ‘fact’, ‘controlled experiment’, ‘scientific method’, ‘theory’, ‘hypothesis’, ‘theory choice’, ‘explanation’, ‘law’, ‘model’, ‘cause’, etc. As soon as students discuss and teachers explicate the meaning of these terms, and related concepts, then philosophy has begun. And the more their meaning, and conditions for correct usage, is investigated then the more sophisticated a student’s philosophising becomes. The pupil who asks: ‘Miss, if no one has seen atoms, how come we are drawing pictures of them?’ has raised just one of the countless philosophical questions to which science gives rise (the relationship of models to reality). Likewise the student who wants to know whether after seeing 20 white swans they can conclude that ‘all swans are white’ touches upon another enduring philosophical dispute (the problem of induction and evidential support for theory). Similarly the student who, having been told about the force of gravitational attraction that exists between bodies, asks why we cannot see it, touch it, smell it or trip over it is highlighting yet another core philosophical issue (the realist versus instrumentalist debate about theoretical terms).[74]

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[71] This was Lenin’s argument against supposed idealist movements in early twentieth-century science and philosophy (Lenin 1920/1970). On the history and philosophy of materialism, see Vitzthum (1995).

[72] On emergent materialism, see Broad (1925), Bunge (1977, 1981), and Sellars (1932).

[73] See at least Erduran and Jiménez-Aleixandre (2008), Cobern (1991, 1996), Yasri et al. (2013), Preston and Epley (2009), Taber et al. (2011), and Stolberg (2007).

[74] For further discussion of the role of philosophy in science teaching, see Matthews (1994/2014, Chap. 5).

With knowledgeable teachers, all of these questions can be further explored, elaborated and connected to studies in other subjects such as economics, history, theology and so on. And such philosophical preparation or exercises can usefully lead on to the more profound questions concerning science, worldviews and religion; without philosophical and historical preparation, the latter discussion too readily becomes merely the exchange of hot air and the advancement of not much at all.

50.11.1 From Physics to Metaphysics: The Law of Inertia

Consider the law of inertia and its related concept of force. The law is the foundation stone of classical physics which is taught in school to every science student. A representative textbook statement is:

> Every body continues in its state of rest or of uniform motion in a straight line except in so far as it is compelled by external impressed force to change that state. (Booth and Nicol 1931/1962, p. 24)

It might be 'demonstrated' by means of sliding a puck on an air table and a puck on an ice sheet or by utilising a version of Galileo's inclined plane demonstration.[75] In a purely technical science education, the law is learnt by heart, and problems worked out using its associated formulae: $F = ma$.

Technical purposes might be satisfied with correct memorisation and mastery of the quantitative skills – 'a force of X newtons acts on a mass of Y kilograms, what acceleration is produced?' – but the goals of liberal education cannot be so easily satisfied.

Just a little philosophical reflection and historical investigation on this routine topic of inertia opens up whole new scientific and educational vistas. The medieval natural philosophers were in the joint grip of Aristotle's physics and of common sense beliefs resulting from their routine everyday experience; indeed Aristotle's physics was more or less just the sophisticated articulation of common sense. Aristotle's empiricism is evident when he says that 'if we cannot believe our eyes what can we believe'. A contemporary Aristotelian says that:

> Aristotle began where everyone should begin – with what he already knew in the light of his ordinary, commonplace experience. …. Aristotle's thinking *began* with common sense, but it did not *end* there. It went much further. It added to and surrounded common sense with insights and understandings that are not common at all. (Adler 1978, pp. xi, xiii)

These understandings resulted in the medieval commitment to the principle of *Omne quod movetur ab alio movetur*: the famous assertion of Aristotle, Aquinas and all the Scholastics which translates as 'Whatever is moved is moved by another (the motor)' and its inverse, if a motor ceases to act, then motion ceases. The principle

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[75] On Galileo's inclined plane experiments, see Palmieri (2011); on their classroom use, see Turner (2012).

grew out of daily experience, common sense and Aristotle's physics. Clagett summarised Aristotle's conviction as:

> for Aristotle motion is a process arising from the continuous action of a source of motion or 'motor' and a 'thing moved'. The source of motion or motor is a force – either internal as in natural motion or external as in unnatural [violent] motion – which during motion must be in contact with the thing moved. (Clagett 1959, p. 425)

Given the fact of motion in the world, then the principle led Aristotle to the postulation of a First Mover. Aquinas and the Scholastics took over this argument and made it an argument for the existence of a prime mover who they identified as God.[76]

Medieval impetus theory was an elaboration of Aristotelian physics: The mover gave something (impetus) to the moved which kept it in motion when the mover was no longer acting (the classic case of a thrown projectile). Some, like da Marchia, thought this impetus naturally decayed, and hence the projectile's motion eventually ceased. Others, like Buridan, thought that the transferred power was only diminished when it performed work, and as pushing aside air was work, then the projectile's motion would also eventually cease. Both theories were consistent with the phenomena: When a stone is thrown from the hand it goes only so far then drops to the ground.[77] Galileo performed a thought experiment by thinking through Buridan's theory to the circumstance of there being no work performed, in which case the projectile once impressed with impetus (force in modern speak) would continue moving forever. But for Galileo it would follow the Earth's contour. He repeated this circumstance with his experiment of a ball rolling down one incline and up another; as the second plane was gradually lowered towards horizontal, the ball moved further and further along it. He supposed that with the smoothest plane and the most polished ball, the ball would just keep moving on the second plane when horizontal; this was the visualisation of his theory of circular inertia.[78]

Galileo had no idea of a body being able to move off the Earth in a straight line away into an infinite void. Like everyone else, Galileo was both physically and conceptually anchored to the Earth. It was only Newton who would make this massive conceptual leap sufficient to have a projectile leave the Earth and move in an infinite void; he moved conceptually from a 'Closed World to the Infinite Universe' (Koyré 1957); by doing so Newton laid the foundation of modern mechanics. The whole 2000-year history of the development of the law of inertia reveals a good deal about the structure and mechanisms of the scientific enterprise, including the process of theory generation and theory choice.[79] Working through this history of argument bears fruit for arguments about worldviews and science.

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[76] See the elaborate and informative discussion in Buckley (1971).

[77] The classic works on medieval impetus theory are Clagett (1959) and Moody (1975).

[78] The classic treatment is Clavelin (1974).

[79] See Ellis (1965) and Hanson (1965) for excellent discussion of Newton's formulation of inertia. On force, see Ellis (1976), Hesse (1961), Hunt and Suchting (1969), and Jammer (1957).

Apart from interesting and important history, basic matters of philosophy arise in any good classroom treatment of the law of inertia and the concept of force:

Epistemology – we never see force-free behaviour in nature nor can it be experimentally induced, so what is the source and justification of our knowledge of bodies acting without impressed forces?
Ontology – we do not see or experience force apart from its manifestation, so does it have existence? What is mass? What is a measure of mass as distinct from weight?
Cosmology – does such an inertial object go on forever in an infinite void? What happens at the limits of 'infinite' space? Were bodies created with movement?

These are the sorts of considerations that prompted Poincaré to say: 'When we say force is the cause of motion, we are talking metaphysics' (Poincaré 1905/1952, p. 98). And as every physics class talks of force being the cause of acceleration, then there is metaphysics lurking in every classroom, just waiting to be exposed by students who are encouraged to think carefully about what they are being taught and by teachers who know something of the history and philosophy of the subject they teach. Such exposition and engagement of school classes in the fundamental ontological, epistemological and methodological matters of philosophy that are occasioned by teaching and learning the law of inertia can be seen in a number of excellent texts.[80] In a recent publication, Ricardo Lopes Coelho discusses both the historical and pedagogical literature on this topic (Coelho 2007). All of this prepares the ground for a more nuanced and informed discussion of the big issues of science, worldviews and religion.

Thinking carefully and historically about basic principles and concepts is a quite general point about the intelligent and competent mastery of any discipline, be it Mathematics, History, Psychology, Literature, Theology, Economics or anything else. They all have their own, and overlapping, concepts and standards for identifying good and bad practice and judgements; consequently there are philosophical questions (epistemological, ontological, methodological and ethical) about each discipline; there is a philosophy of each discipline. The intelligent learning of any discipline requires some appropriate interest and competence in its philosophy; that is simply what 'learning with understanding' means – an obvious educational point made by Ernst Mach (1886/1986) and more recently by Israel Scheffler (1970).[81] If serious scientists, such as listed earlier in this chapter, feel it important to write books on the philosophy of their subject, then assuredly science teachers and students will benefit from following their example and engaging with the same questions.

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[80] See especially those of Arnold Arons (Arons 1977, Chaps.14–15; 1990, Chap. 3), Gerald Holton and Stephen Brush (Holton and Brush 2001, Chap. 9) and the Harvard Project Physics texts (Holton et al. 1970).

[81] Mach's argument is discussed in Matthews (1989b), and Scheffler's argument is discussed in Matthews (1997).

The arguments of Mach and Scheffler have belatedly and independently found expression in the wide international calls for students to learn about the ‘nature of science’ while learning science. One cannot learn about the nature of science without learning philosophy of science, which was precisely Mach and Scheffler’s argument.

50.12 Conclusion

Science has contributed immensely to our philosophical and cultural tradition, this is part of the ‘flesh’ of science; however too often science teaching presents just the ‘bare bones’ of laws, formulae and problems, the ‘final products’ of science. This is one reason why, notoriously, advanced ‘technical’ science is so often associated with religious and ideological fundamentalism and bigotry.[82] The cultural flesh of science should be part of any serious science programme.

Carl Sagan’s undergraduate experience at the University of Chicago in the 1950s is no longer available to many students, but it is worth recalling as an ideal and something which might be striven for:

> At the University of Chicago I also was lucky enough to go through a general education program devised by Robert M. Hutchins, where science was presented as an integral part of the gorgeous tapestry of human knowledge. It was considered unthinkable for an aspiring physicist not to know Plato, Aristotle, Bach, Shakespeare, Gibbon, Malinowski, and Freud – among many others. In an introductory science class, Ptolemy’s view that the Sun revolved around the Earth was presented so compellingly that some students found themselves re-evaluating their commitment to Copernicus. … I also witnessed at first hand the joy felt by those whose privilege it is to uncover a little about how the Universe works. (Sagan 1996, pp. xiv-xv)

In a good liberal education, science students, and hopefully other students as well, will learn about the philosophical dimensions of science, beginning with routine matters such as conceptual analysis, epistemology, values and so on. They will also learn about the metaphysical, especially ontological, dimensions of science, some of which have been discussed above. They should also be introduced to and hopefully make decisions about the constitution and applicability of the scientific outlook, habit of mind or the scientific temper. To entertain questions such as: Is a scientific outlook required for the solution of social and ideological problems? By reading about any number of courageous scientists beginning with Galileo and moving through Joseph Priestley and on to Andrei Sakharov (Sakharov 1968), students can be introduced to the issue of the social and cultural requirements for the pursuit of science, the issue that so animated the Enlightenment scientists, philosophers and social reformers.

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[82] That there is no connection between advanced technology and advanced thinking was sadly demonstrated when numerous spectators to the Papua New Guinea witch burning described above captured the event on their mobile phone cameras and uploaded the burning onto the World Wide Web.

In particular students might think through and re-argue the Enlightenment tradition's claims that on purely epistemological grounds, science, and more generally the pursuit of truth in all human domains, requires legal protection of free speech, freedom of the press and support for diversity, unhindered scholarly publication and freedom of association. To entertain questions such as: Does the promotion and spread of science entail a liberal, secular, democratic, non-authoritarian state?

All of this makes science classes more intellectually engaging, it promotes 'minds-on' science learning, and it enables diverse subjects in a school curriculum (history, mathematics, technology, religion) to be related. The introduction of history and philosophy to science lessons enables students to better understand the science and the scientific methodology they are learning, to better appreciate the role of science in the formation of the modern world and contemporary worldviews and perhaps the knowledge and enthusiasm to support science and the spread of the 'scientific habit of mind'.

Undoubtedly such an education has an impact on, and contributes to, the world-views of students. So it is worth noting Frederick Copleston's caution:

> It must be recognized, I think, that the creation of world-views is none the less a pretty risky procedure. There is, for example, the risk of making unexamined or uncriticized presuppositions in a desire to get on with the painting of the picture. Again, there are the risks of over-hastily adopting desired conclusions, and also of allowing one's judgements to be determined by personal prejudices or psychological factors. (Copleston 1991, p. 71)

But science teachers are not so much creating worldviews but encouraging students to identify and then to begin to analyse and appraise aspects of worldviews. For educators, it is the student's inquiry and thinking that is important. A good science teacher can agree with Bertrand Russell who famously said in 1916 at the height of the Great War when he criticised the use of schools by both sides for nationalist indoctrination:

> Education would not aim at making them [students] belong to this party or that, but at enabling them to choose intelligently between the parties; it would aim at making them able to think, not at making them think what their teachers think. (Egner and Denonn 1961, pp. 401–402)

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Chapter 51
What Significance Does Christianity Have for Science Education?

Michael J. Reiss

51.1 Introduction

Worldwide, religion remains of importance to many people, including young people; a survey undertaken in 2011 in 24 countries found that 73 % of respondents under the age of 35 (94 % in primarily Muslim countries and 66 % in Christian majority countries) said that they had a religion/faith and that it was important to their lives (Ipsos MORI 2011).

Furthermore, to the bemusement of many science educators in school and elsewhere, and the delight of some, issues to do with religion seem increasingly to be of importance in school science lessons, science museums and some other educational settings. This chapter begins by examining the nature of religion in general and Christianity in particularly and then examines the nature of science before looking at possible ways in which religion in general and Christianity in particular might relate to science. The chapter then considers whether or not Christianity has implications for science education and, if it does, how teaching might take account of Christian belief.

To many science educators even raising the possibility that religion might be considered within science education raises suspicions that this is an attempt to find a way of getting religion into the science classroom for religious rather than scientific reasons. This is not the intention here. In terms of the nature of science, part of the argument is that considering religion can be, on occasions, useful simply for helping learners better understand why certain things come under the purview of science and others don't.

Another argument for considering religion within science education proceeds much as an argument for considering history in science education might. While

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science can be learnt and studied in a historical vacuum, there are a range of arguments for examining science in its historical contexts. For a start, this helps one understand better why certain sorts of science were pursued at certain times. Wars, for instance, have sometimes led to advances in chemistry, physics and information science (e.g. explosives, missile trajectories, code breaking), while certain botanical disciplines, such as systematics and taxonomy, have flourished during periods of colonisation. Much biology is studied in the hope that medical advances will ensue, so studies of anatomy have developed into studies of physiology and, more recently, genetics and molecular biology. Then there is the observation that for many learners understanding science in historical context can aid motivation. Science courses that take contexts and applications into account are now quite widespread (cf. the whole STS movement even if the jury is still out as to the consequences for the understanding of science concepts).

Similarly, while many students enjoy learning about the pure science of genetics and evolution, otherwise are motivated and come to understand the science better if they appreciate something of the diversity of religious beliefs held by such principal protagonists as Charles Darwin, Joseph Hooker, Thomas Huxley and Gregor Mendel and the religious views (including the diversity of religious views) of the cultures in which they lived and worked.

There are a number of places where religion and science interact. Consider, first, the question of 'authority' and the scriptures as a source of authority. To the great majority of religious believers, the scriptures of their religion (the Tanakh, the Christian bible, the Qur'an, the Vedas, including the Upanishads, the Guru Granth Sahib, the various collections in Buddhism) have an especial authority by very virtue of being scripture. This is completely different from the authority of science. Newton's *Principia* and Darwin's *On the Origin of Species* are wonderful books, but they do not have any permanence other than that which derives from their success in explaining observable phenomena of the material world and enabling people to see the material world through Newtonian/Darwinian eyes. Indeed, as is well known, Darwin knew almost nothing of the mechanism of inheritance despite the whole of his argument relying on inheritance, so parts of *The Origin* were completely out of date over 100 years ago.

Then consider the possibility of miracles, where the word is used not in its everyday sense (and the sense in which it is sometimes used in the Christian scriptures), namely, 'remarkable', 'completely unexpected' or 'wonderful' (as in the tabloid heading 'My miracle baby'), but in its narrower meaning of 'contrary to the laws of nature'. Scientists who do not accept the occurrence of miracles can react to this latter notion of miracles in one of the three ways: (i) miracles are impossible (because they are contrary to the laws of nature); (ii) miracles are outside of science (because they are contrary to the laws of nature) and (iii) miracles are very rare events that have not yet been incorporated within the body of science but will be (as rare meteorological events, e.g. eclipses, and mysterious creatures, e.g. farm animals with two heads or seven legs, have been).

This chapter addresses such issues. It focuses on Christianity because other chapters in this volume address others of the world's major religions. At the same time, without wishing to appear triumphalistic or colonial, there are some particular reasons why Christianity deserves consideration in its own right. For a start, and without negating the importance of science to all cultures, and the especial roles in its origins and development played in China and by Islam, Christianity played a major role in the origin of modern science. Historians appear broadly to agree on this although there is continuing debate about other influences and the relative contributions of each (Brooke 1991; Harrison 2001; Hooykaas 1972).

Then there is the fact that throughout the history of science, many scientists have been Christians and have seen their faith as supporting their science. In a sense this is a trivial point given that a large proportion of the population was Christian in the countries where modern science principally arose (i.e. Western Europe). Less trivial is the point that some of these scientists tackled certain scientific issues in ways that connected to their faith, though this is less the case nowadays when there is far more of a clear-cut separation between a scientist's beliefs and their science. A thorough history of science can only be developed if the significance of Christianity for certain scientists is acknowledged. Standard instances include Robert Boyle (e.g. Hunter 2009; MacIntosh 2006), Michael Faraday (e.g. Russell 2000) and Georges Lemaître (Farrell 2005).

The Christian faith represents a significant worldview in many countries, though substantially less so nowadays in Western Europe than in the past. It has helped to shape many modern institutions and provides a framework that exists in contrast to the materialism which is also widespread in many contemporary societies and classrooms. Gauch (2009) argues that 'the presuppositions and reasoning of science can and should be worldview independent, but empirical and public evidence from the sciences and humanities can support conclusions that are worldview distinctive' (p. 27).

Finally, there is the obvious point that there are a number of instances where science and Christianity intersect, whether in the classroom or wider public discourse. One clear instance is the creationism-evolution 'debate'; another is to do with such bioethical issues as the acceptability of genetic engineering, euthanasia, stem cell research and cloning; and another is to do with such philosophical issues as determinism. The importance of Christian theology and practice, noting that the situation is complicated/enriched by the fact that there is rarely a single Christian voice, for debates about determinism, evolution and bioethics are considered below.

51.2 The Nature of Religion

There are many religions, and it is difficult to answer the question 'What is the nature of religion?' in a way that satisfies the members of all religions. Nevertheless, the following, derived from Smart (1989) and Hinnells (1991), are generally characteristic of most religions (Reiss 2008a):

> Religions have a *practical and ritual dimension* that encompasses such elements as worship, preaching, prayer, yoga, meditation and other approaches to stilling the self.
>
> The *experiential and emotional dimension* of religions has at one pole the rare visions given to some of the crucial figures in a religion's history, such as that of Arjuna in the *Bhagavad Gita*, the revelation to Moses at the burning bush in *Exodus* and Saul on the road to Damascus in *Acts*. At the other pole are the experiences and emotions of many religious adherents, whether a once-in-a-lifetime discernment of the transcendent or a more frequent feeling of the presence of God either in corporate worship or in the stillness of one's heart.
>
> All religions hand down, whether orally or in writing, vital stories that comprise the *narrative or mythic dimension*, for example the story of the birth, life, death, resurrection and ascension of Jesus in the Christian scriptures. For some religious adherents such stories are believed literally, for others they are understood symbolically.
>
> The *doctrinal and philosophical dimension* arises, in part, from the narrative/mythic dimension as theologians within a religion work to integrate these stories into a more general view of the world. Thus the early Christian church came to its understanding of the doctrine of the Trinity by combining the central claim of the Jewish religion – that there is but one God – with its understanding of the life and teaching of Jesus Christ and the working of the Holy Spirit.
>
> If doctrine attempts to define the beliefs of a community of believers, the *ethical and legal dimension* regulates how believers act. So Sunni Islam has its Five Pillars, while Judaism has the Ten Commandments and other regulations in the Torah and Buddhism its Five Precepts.
>
> The *social and institutional dimension* of a religion relates to its corporate manifestation, for example the Sangha – the order of monks and nuns founded by the Buddha to carry on the teaching of the Dharma – in Buddhism, the umma' – the whole Muslim community – in Islam, and the Church – the communion of believers comprising the body of Christ – in Christianity.
>
> Finally, there is the *material dimension* to each religion, namely the fruits of religious belief as shown by places of worship (e.g. synagogues, temples and churches), religious artefacts (e.g. Eastern Orthodox icons and Hindu statues) and sites of special meaning (e.g. the river Ganges, Mount Fuji and Uluru (Ayers Rock)).

As will be discussed below, the relationship between science and religion has changed over the years (Al-Hayani 2005; Brooke 1991; Szerszynski 2005); indeed, the use of the singular, 'relationship', risks giving the impression that there is only one way in which the two relate. Nevertheless, there are two key issues: one is to do with understandings of reality and the other to do with evidence and authority. Although it is always desperately difficult to generalise (difficult in the sense that one lays oneself open to accusations that one hasn't considered every particular – and yet the alternative is to be submerged in a weight of detail that would surely suffocate all but the most devoted/obsessive of readers), most religions hold that reality consists of more than the objective world, and many religions give weight to personal and/or (depending on the religion) institutional authority in a way that science generally strives not to.

For example, there is a very large religious and theological literature on the world to come, i.e. life after death, (e.g. Hick 1976/1985). However, to labour the point, although some (notably Atkins 2011) have argued that science disproves the existence of life after death, it can be objected that science, strictly speaking, has little or nothing to say about this question because life after death exists or would exist outside of or beyond the realm to which science relates. Furthermore, many religious believers within a particular religion are likely to find the pronouncements on the question of life after death by even the most intelligent and spiritual of their present leaders (let alone reputable scientists) to be of less significant than the few recorded words of their religion's founder(s). In the case of Christianity, while the proportion of believers who take literally the resurrection promises of the New Testament may be less than in previous ages (though high-quality comparative quantitative data are unavailable), it remains the case that literal belief in an afterlife is widespread among believers.

Before moving on to the nature of science, it is worth, in this section on the nature of religion, briefly saying something specifically about the nature of Christianity. While there are many Christian denominations, they all treat the Jewish scriptures and the New Testament as jointly constituting their scriptures, though there are differences as to which books are included in the Christian 'Old Testament'. The core beliefs of Christianity are summed up in the books of the New Testament and subsequent formulations such as the Apostles' and Nicene Creeds. The most widely recited formulation is the Nicene Creed which, in its 1975 ecumenical version, reads:

> We believe in one God,
> the Father, the Almighty
> maker of heaven and earth,
> of all that is, seen and unseen.
> We believe in one Lord, Jesus Christ,
> the only Son of God,
> eternally begotten of the Father,
> God from God, Light from Light,
> true God from true God,
> begotten, not made,
> of one Being with the Father.
> Through him all things were made.
> For us and for our salvation
> he came down from heaven:
> by the power of the Holy Spirit
> he became incarnate from the Virgin Mary, and was made man.
> For our sake he was crucified under Pontius Pilate;
> he suffered death and was buried.
> On the third day he rose again
> in accordance with the Scriptures;
> he ascended into heaven
> and is seated at the right hand of the Father.
> He will come again in glory to judge the living and the dead,
> and his kingdom will have no end.
> We believe in the Holy Spirit, the Lord, the giver of Life,
> who proceeds from the Father and the Son.
> With the Father and the Son he is worshipped and glorified.
> He has spoken through the Prophets.
> We believe in one holy catholic and apostolic Church.
> We acknowledge one baptism for the forgiveness of sins.
> We look for the resurrection of the dead,
> and the life of the world to come. Amen. (Episcopal Church 1979)

It is evident that some of the issues addressed in the Nicene Creed are to do with science and some are not. However, even those that at first appear not to be (e.g. the Trinity) have been examined from a science and religion perspective (e.g. Polkinghorne 2004). Indeed, if we restrict ourselves to those features of Christianity that are central to the science-religion issue, these include a belief that the triune God who creates, sustains and redeems the world is non-capricious (i.e. there are laws of nature) and deeply concerned with the created order (Poole 1998).

51.3 The Nature of Science

The term 'nature of science' is understood in a number of ways, as discussed elsewhere in this volume, but at its heart is knowledge about how, and to a lesser extent why, science is undertaken. So the nature of science includes issues about the fields of scientific enquiry and the methods used in that enquiry as well as, to a certain extent, something about the purpose of science.

A key point about the fields of scientific enquiry is that these have shifted over time. In large measure this is simply because of developments in instrumentation. We can now study events that happen at very low temperatures, at distances, at speeds and at magnifications that simply were not possible even a few decades ago. What is still unclear is the extent to which certain matters currently outside of mainstream science will one day fall within the compass of science. Take dreams, for example. It may be that these will remain too subjective for science, but it may be that developments in the recording of brain activity will mean that we can obtain a sufficiently objective record of dreams for them to be amenable to rigorous scientific study.

But the scope of science has also shifted for reasons that are more to do with theorisation than with technical advances (Reiss 2013a). Consider beauty. Aesthetics for a long time was not considered a scientific field. But there is now, within psychology and evolutionary biology, growing scientific study of beauty and desire (e.g. Buss 2003). Indeed, a number of the social sciences are being nibbled away at by the natural sciences, and if one believes some scientists, almost the only valid knowledge is scientific knowledge (Atkins 2011).

Despite such movements in the fields of scientific enquiry and in the actual methods employed by scientists, the overarching methods of science (what a social scientist might term its methodology) have shifted far less, certainly for several hundreds of years, arguably for longer than that.

As is well known, Robert Merton characterised science as open-minded, universalist, disinterested and communal (Merton 1973). For Merton, science is a group activity; even though certain scientists work on their own, science, within its various subdisciplines, is largely about bringing together into a single account the contributions of many different scientists to produce an overall coherent model of one aspect of reality. In this sense, science is (or should be) impersonal. Allied to the notion of science being open-minded, disinterested and impersonal is the notion of scientific objectivity. The data collected and perused by scientists must be objective in the sense that they should be independent of those doing the collecting (cf. Daston and Galison 2007) – the idealised 'view from nowhere'. This is the main reason why the data obtained by psychotherapists are (at least at present) not really scientific: they depend too much on the specifics of the relationship between the therapist and the client. The data obtained by cognitive behavioural therapists, on the other hand, are more scientific (cf. Salkovskis 2002).

Karl Popper emphasised the falsifiability of scientific theories (Popper 1934/1972): unless one can imagine collecting data that would allow one to refute a theory, the theory isn't scientific. The same applies to scientific hypotheses. So, iconically, the hypothesis 'All swans are white' is scientific because we can imagine finding a bird that is manifestly a swan (in terms of its anatomy, physiology and behaviour) but is not white. Indeed, this is precisely what happened when early White explorers returned from Australia with tales of black swans.

Popper's ideas easily give rise to a view of science in which knowledge accumulates over time as new theories are proposed and new data collected to distinguish between conflicting theories. Much school experimentation in science is Popperian: we see a rainbow and hypothesise that white light is split up into light of different colours as it is refracted through a transparent medium (water droplets); we test this by attempting to refract white light through a glass prism; we find the same colours of the rainbow are produced, and our hypothesis is confirmed. Until some new evidence causes it to be falsified, we accept it (Reiss 2008a).

Thomas Kuhn made a number of seminal contributions, but he is most remembered nowadays for his argument that while the Popperian account of science holds well during periods of normal science when a single paradigm holds sway, such as the Ptolemaic model of the structure of the solar system (in which the Earth is at the centre) or the Newtonian understanding of motion and gravity, it breaks down when a scientific crisis occurs (Kuhn 1970). At the time of such a crisis, a scientific revolution happens during which a new paradigm, such as the Copernican model of the structure of the solar system or Einstein's theory of relativity, begins to replace (initially to coexist with) the previously accepted paradigm. The central point is that the change of allegiance from scientists believing in one paradigm to their believing in another cannot, Kuhn argues, be fully explained by the Popperian account of falsifiability.

A development of Kuhn's work was provided by Lakatos (1978) who argued that scientists work within research programmes. A research programme consists of a set of core beliefs surrounded by layers of less central beliefs. Scientists are willing to accept changes to these more peripheral beliefs so long as the core beliefs can be defended. So, in biology, we might see in contemporary genetics a core belief in the notion that development proceeds via a set of interactions between the actions of genes and the influences of the environment. At one point, it was thought that the passage from DNA to RNA was unidirectional. Now we know (reverse transcriptase, etc.) that this is not always the case. The core belief (that development proceeds via a set of interactions between the actions of genes and the influences of the environment) remains unchanged, but the less central belief (that the passage from DNA to RNA is unidirectional) is abandoned.

The above account of the nature of science portrays science as what John Ziman (2000) has termed 'academic science'. Ziman argues that such a portrayal was reasonably valid between about 1850 and 1950 in European and American universities but that since then we have entered a phase largely characterised by 'post-academic science'. Post-academic science is increasingly transdisciplinary and utilitarian, with a requirement to produce value for money. It is more influenced by politics, it is more industrialised and it is more bureaucratic. The effect of these changes is to make the boundaries around the domain of science a bit fuzzier. Of course, if one accepts the contributions of the social study of science (e.g. Yearley 2005), one finds that these boundaries become fuzzier still. The argument in this chapter does not *rely* on such a reading of science though someone who is persuaded by the 'Strong Programme' within the sociology of scientific knowledge (i.e. the notion that even valid scientific theories are amenable to sociological investigation of their truth claims) is much more likely to accept the worth of science educators considering the importance of religion as one of many factors that influence the way science is practised and scientific knowledge produced.

51.4 Understandings of Possible Relationships Between Science and Religion

It is clear that there can be a number of axes on which the science-religion issue can be examined. For example, the effects of the practical and ritual dimension are being investigated by scientific studies that examine such things as the efficacy of prayer and the neurological consequences of meditation (e.g. Lee and Newberg 2005); a number of analyses of religious faith, informed by contemporary understandings of evolutionary psychology, behavioural ecology and sociobiology, examine the possibility or conclude that religious faith can be explained by science (e.g. Dennett 2006; Hinde 1999; Reynolds and Tanner 1983); the narrative/mythic dimension of religion clearly connects (in ways that will be examined below) with scientific accounts of such matters as the origins of the cosmos and the evolution of life; the doctrinal and philosophical dimension can lead to understandings that may agree or disagree with standard scientific ones (e.g. about the status of the human embryo); and the ethical and legal dimension can lead to firm views about such matters as land ownership, usury and euthanasia.

Perhaps only the social and institutional and the material dimensions of religion are relatively distinct from the world of science (understand as the natural sciences rather than the social sciences more broadly), in that science has little if anything to say about such manifestations of religion – i.e. in Christianity, the Church and such things as religious artefacts.

There is now a very large literature on the relationship between science and religion (a major overview is provided by Clayton and Simpson 2006). Indeed, the journal *Zygon* specialises in this area, while *Science & Christian Belief* focuses on the relationship between science and Christianity. A frequent criticism by those who write in this area (e.g. Roszak 1994 and regular articles by Andrew Brown and Paul Vallely in the *Church Times*) is of what they see as simplistic analyses of the area by those, often renowned scientists, who write occasionally about it. Indeed, it is frequently argued that the clergy both in the past and nowadays are often far more sympathetic to a standard scientific view on such matters as evolution than might be supposed (e.g. Colburn and Henriques 2006).

A particularly thorough historical study of the relationship between science and religion is provided by John Hedley Brooke (1991). Brooke's aim is 'to reveal something of the complexity of the relationship between science and religion as they have interacted in the past' (p. 321). He concludes:

> Popular generalizations about that relationship, whether couched in terms of war or peace, simply do not stand up to serious investigation. There is no such thing as *the* relationship between science and religion. It is what different individuals and communities have made of it in a plethora of different contexts. Not only has the problematic interface between them shifted over time, but there is also a high degree of artificiality in abstracting the science and the religion of earlier centuries to see how they were related. (Brooke 1991, p. 321)

Perhaps the best known categorisation of the ways in which the relationship between science and religion can be understood was provided by Ian Barbour (1990). Barbour himself updated this book (Barbour 1997), and since 1990 there has been a considerable literature about the ways in which science and religion relate (e.g. Glennan 2009; Haught 1995; Plantinga 2010; Stenmark 2004); indeed, Mark Vernon argues that rather more agnosticism and less dogmatism in the science-religion field would be wise (Vernon 2008). Nevertheless, Barbour's (1990) typology continues to dominate the literature and so is employed here. Barbour, who focuses especially on epistemological assumptions of recent Western authors, identifies four main groupings.

First, there is the relationship of *conflict*; 'first' simply because it is the first in Barbour's list and first, perhaps, also in the minds of many people, whether or not they have a religious faith (cf. McGrath 2005). Barbour doesn't give a reason for the order of his listing, but at least two can be suggested: comprehensibility and familiarity. It is both easy and familiar (given Barbour's declared focus on recent Western authors) to see the relationship between science and religion as one of conflict. However, as one might expect from a professor of science, technology and society giving the Gifford lectures (the result of an 1885 bequest of £80,000 'for the establishment of a series of lectures dealing with the topic of natural religion' (Gifford lectures 2006)), Barbour sees limitations in this way of understanding the science-religion issue. As he memorably puts it:

> In a fight between a boa constrictor and a wart-hog, the victor, whichever it is, swallows the vanquished. In scientific materialism, science swallows religion. In biblical literalism, religion swallows science. The fight can be avoided if they occupy separate territories or if, as I will suggest, they each pursue more appropriate diets. (Barbour 1990, p. 4)

Barbour's second grouping is *independence* (e.g. Gould 1999). Science and religion may be seen as independent for two main reasons: because they use distinctive methods or because they function as different languages. In any event, the result is that each is seen as distinct from the other and as enjoying its own autonomy:

> Each has its own distinctive domain and its characteristic methods that can be justified on its own terms. Proponents of this view say there are two jurisdictions and each party must keep off the other's turf. Each must tend to its own business and not meddle in the affairs of the others. Each mode of inquiry is selective and has its limitations. (Barbour 1990, p. 10)

Barbour's third grouping moves beyond conflict and independence to *dialogue* (cf. Berry 1988; Polkinghorne 2005; Watts 1998; Williams 2001). As an example of dialogue, Barbour points out how our understanding of astronomy has forced us to ask why the initial conditions were present that allowed the universe to evolve. The point is not that the findings of science require a religious faith – that would be for the warthog of religion to swallow the boa constrictor of science. Rather the point is that scientific advances can give rise (no claim is made that they do for all people) to religious questions, so that a dialogue ensues.

Barbour's final grouping is one in which the relationship between science and religion is seen to be one of *integration* (cf. Peacocke 2001; Polkinghorne 1994). For example, in natural theology it is held that the existence of God can be deduced from aspects of nature rather than from revelation or religious experience (e.g. Ray 1691/2005). Natural theology has rather fallen out of favour (but see Polkinghorne 2006). A more modern version is process theology which rejects a view of the world in which purely natural events (characterised by an absence of divine activity) are interspersed with occasional gaps where God acts. Rather, for process theologians, every event is understood 'to be jointly the product of the entity's past, its own action, and the action of God' (Barbour 1990, p. 29). Furthermore, God is not the Unmoved Mover of Thomas Aquinas but instead acts reciprocally with the world.

I think it can be difficult for those who have never had a religious faith, or have only had one rather tenuously, to imagine what a life is like that is lived wholly within a religious ordering. For such a person, the relationship between science and their faith may be described as 'integrated' though this is to give an epistemological framing to the relationship, whereas what may be going on is that the person has little overt interest in the precise nature of the relationship between science and religion other than that there can clearly be no conflict between them.

Anthropologists provide good accounts of what it can be like to live a life where one's religious faith integrates with every aspect of one's life. One of my favourite such accounts is that of du Boulay (2009) who studied life in a Greek Orthodox Village in the late 1960s and early 1970s. Everything that happened in the village needs to be understood by reference to Greek Orthodoxy. To give just one instance, the annual liturgical and agricultural cycles intermeshed, so that after the harvest, the sowing of the seed for next year's harvest was closely related to the Christian calendar:

> The main sowing of the wheat is carried into November, and the Archangel Michael, celebrated on 8 November and seen on his icons with drawn sword, is a formidable figure associated with the darkening November days with the leaves being stripped from the trees and the smoke gusting in ashy draughts down the chimneys; but this is a month named after the preeminent agricultural task – 'The Sower' (*Σποριας*). And the Entry of the Mother of

> God into the Temple on 21 November, soon after the Christmas fast has begun, is also in the village given the character of the time as the ‘Mother of God Half-Way-Through-The-Sowing’ (*Παναγια Μισοσπειριτσα*). The task of the sowing of the wheat then continues into the time know as ‘Andrew’s’ (St Andrew, whose day is 30 November, but who has given his name to the following month of December), and can go on up to Christmas – and even beyond, if the weather has not been fit. (du Boulay 2009, p. 106)

Having examined possible relationships between science and religion, and given a flavour of the way in which religion can order a person’s understanding of and immersion in the world, I turn now to the issues of determinism and evolution to discuss at a more fine-grained level how Christianity and science can correlate.

51.5 Determinism

The ‘science-religion issue’ is often examined simply by recourse to certain cause célèbres – Galileo and Copernican heliocentrism, Darwin and evolution and arguments about the sanctity of life, for example. At school level, examinations of such particular instances of the relationship between science and religion, along with a more general consideration about how science and religion can relate, are perfectly appropriate. However, there are certain ‘higher-order’ questions that teachers and curriculum developers need to consider to decide whether they can be introduced meaningfully at school level. One such central question is about whether nature is deterministic and, if it/she is not, whether that has anything to do with divine action. Theologically speaking, this is part of the more general question as to how (for those who have a religious faith) God acts in nature (Dixon 2008).

The post-Newtonian advent in the early twentieth century of quantum theory and, later in the same century, of chaos theory has led many to wonder whether within either or both of these two frameworks might lie a space for divine action in a way that does not contradict the scientific worldview in the way that miracles seem to. For almost anyone who has not studied quantum physics to at least first-degree level, it is exceptionally difficult to understand what is going on that is relevant to the science-religion issue, but a core concept is that of determinism, which results from the issue of the relationship of measurement to reality (e.g. Bhaskar 1978; Osborn 2005).

As is well known, in 1927 Heisenberg argued that certain key physical variables that had previously been presumed to be independent (e.g. the position and momentum of an object) are linked. Measuring the one to a very high degree of precision necessarily means that the other cannot be so precisely determined. Thus far there is not a great deal that is of interest to the non-physicist – the issue appears to be one of epistemology. However,

> Heisenberg himself took a more radical view – he saw this limitation as a property of nature rather than an artefact of experimentalism. This radical interpretation of uncertainty as an ontological principle of indeterminism implies that quantum mechanics is inherently statistical – it deals with probabilities rather than well-defined classical trajectories. Such a view is clearly inimical to classical determinism. (Osborn 2005, p. 132)

Put somewhat loosely, a number of people have tried to find room for divine action in this indeterminacy. No consensus yet exists as to the validity of this search though, on balance, the current views seem to be that such a search is mistaken for reasons both of theology and of physics. A particularly helpful, though demanding, analysis of both the theology and the physics is provided by Saunders (2002). Beginning with the theology, Saunders draws on the widespread distinction between general and special forms of divine action. In the words of Michael Langford, general divine action is 'the government of the universe through the universal laws that control or influence nature, man, and history, without the need for specific or ad hoc acts of divine will' (Langford 1981, p. 11). On the other hand, special divine action is characterised by

> Those actions of God that pertain to a *particular* time and place in creation as distinct from another. This is a broad category and includes the traditional understanding of 'miracles', the notion of particular providence, responses to intercessionary prayer, God's personal actions, and some forms of religious experience. (Saunders 2002, p. 20)

Oversimplifying considerably, all religions are comfortable with the notion of general divine action, but they differ both among and within themselves considerably in their understanding of specific divine action. In particular, many leading theologians (but see Pannenberg 2006) are uncomfortable with the notion of specific divine action so defined for a number of reasons including the particular problems for the occurrence of suffering that it raises (if suffering can sometimes be averted miraculously, why isn't it always or, at least, much more often?) and the apparent shortcomings, including capriciousness, suggested by a divine being who relies on occasional exercises of supernatural activity to keep things moving along (cf. Kenny 1992).

Going onto the physics, Saunders is sceptical of attempts to locate the possibility of specific divine action in quantum or chaos theory. The argument here becomes even more technical and depends, in respect of quantum theory, on whether one accepts the standard (Copenhagen) interpretation of reality (in which Schrödinger's cat is either dead or alive before the box is opened) or the more radical interpretation (in which the cat is both dead and alive). In both cases, though, as well as in the case of chaos theory (sometimes termed 'complexity theory' on the grounds that it deals with systems that are deterministic but unpredictable because of their exquisite sensitivity to small changes in their initial conditions), Saunders rejects attempts to find opportunities for specific divine activity in the science.

51.6 Evolution

51.6.1 The Scientific Consensus Concerning Evolution

As with any large area of science, there are parts of what we might term 'front-line' evolution that are unclear, where scientists still actively work attempting to discern what is going on or has gone on in nature. But much of evolution is not like that. Evolution is a well-established body of knowledge that has built up over 150 years as a result of the activities of many thousands of scientists. The following are examples of statements about evolution that lack scientific controversy:

- All of today's life on Earth is the result of modification by descent from the simplest ancestors over a period of several thousand million years.
- Natural selection is a major driving force behind evolution.
- Evolution relies on those occasional instances of the inheritance of genetic information that help (rather than hinder) its possessor to be more likely to survive and reproduce.
- Most inheritance is vertical (from parents) though some is horizontal (e.g. as a result of viral infection carrying genetic material from one species to another).
- The evolutionary forces that gave rise to humans do not differ in kind from those that gave rise to any other species. (Reiss 2013b)

For those who accept such statements and the theory of evolution, there is much about the theory of evolution that is intellectually attractive. For a start, a single theory provides a way of explaining a tremendous range of observations: for example, why it is that there are no rabbits in the Precambrian, why there are many superficial parallels between marsupial and placental mammals, why monogamy is more common in birds than in fish and why sterility (e.g. in termites, bees, ants, wasps and naked mole rats) is more likely to arise in certain circumstances than in others. Indeed, I have argued elsewhere that evolutionary biology can help with some theological questions, including the problem of suffering (Reiss 2000).

51.6.2 Rejecting Evolution

The theory of evolution is not a single proposition that a person must either wholly accept or wholly reject. At one pole are materialists who, eschewing any sort of critical realist distinction between the empirical, the actual and the real (Bhaskar 1978), maintain that there is no possibility of anything transcendent lying behind what we see of evolution in the results of the historical record (fossils, geographical distributions, comparative anatomy and molecular biology) and today's natural environments and laboratories. At the other pole are the advocates of creationism, inspired by a literal reading of certain scriptures. But in between lie many others (Scott 1999) including those who hold that evolutionary history can be providential as human history is.

In addition, there are a whole set of nonreligious reasons why someone may actively reject aspects of the theory of evolution. After all, it may seem to defy common sense to suppose that life in all its complexity has evolved from non-life. And then there is the tremendous diversity of life we see around us. To many it hardly seems reasonable to presume that giant pandas, birds of paradise, spiders, orchids, flesh-eating bacteria and the editor of this book all share a common ancestor – yet that is what mainstream evolutionary theory holds.

It is, though, for religious reasons that many people reject evolution. Creationism exists in a number of different forms, but between about 10 % of adults in the

Nordic countries and Japan and 50 % of adults in Turkey (40 % in the USA) reject the theory of evolution and believe that the Earth came into existence as described by a literal (i.e. fundamentalist) reading of the early parts of the Bible or the Qur'an and that the most that evolution has done is to change species into closely related species (Lawes 2009; Miller et al. 2006). Christian fundamentalists generally hold that the Earth is nothing like as old as evolutionary biologists and geologists conclude – as young as 10,000 years or so for young Earth creationists. For Muslims, the age of the Earth is much less of an issue.

Allied to creationism is the theory of intelligent design. While many of those who advocate intelligent design have been involved in the creationism movement, to the extent that the US courts have argued that the country's First Amendment separation of religion and the State precludes its teaching in public schools (Moore 2007), intelligent design can claim to be a theory that simply critiques aspects of evolutionary biology rather than advocating or requiring religious faith. Those who promote intelligent design typically come from a conservative faith-based position (though there are atheists who accept intelligent design). However, in their arguments against evolution, they typically make no reference to the scriptures or a deity but argue that the intricacy of what we see in the natural world, including at a subcellular level, provides strong evidence for the existence of an intelligence behind this (e.g. Meyer 2009). An undirected process, such as natural selection, is held to be incapable of explaining all such intricacy.

51.6.3 Evolution in School Science

Few countries have produced explicit guidance as to how schools might deal with the issues of creationism or intelligent design in the science classroom. One country that has is England (Reiss 2011). In the summer of 2007, the then DCSF (Department of Children, Schools and Families) Guidance on Creationism and Intelligent Design received Ministerial approval and was published (DCSF 2007). The Guidance points out that the use of the word 'theory' in science (as in 'the theory of evolution') can mislead those not familiar with science as a subject discipline because it is different from the everyday meaning, when it is used to mean little more than an idea.

The DCSF Guidance goes on to state 'Creationism and intelligent design are sometimes claimed to be scientific theories. This is not the case as they have no underpinning scientific principles, or explanations, and are not accepted by the science community as a whole' (DCSF 2007) and then says:

> Creationism and intelligent design are not part of the science National Curriculum programmes of study and should not be taught as science. However, there is a real difference between teaching 'x' and teaching *about* 'x'. Any questions about creationism and intelligent design which arise in science lessons, for example as a result of media coverage, could provide the opportunity to explain or explore why they are not considered to be scientific theories and, in the right context, why evolution is considered to be a scientific theory. (DCSF 2007)

This is a key point and one that is independent of country, whether or not a country permits the teaching in schools of religion (as in the UK) or does not (as in France, Turkey and the USA). Many scientists, and some science educators, fear that consideration of creationism or intelligent design in a science classroom legitimises them. For example, the excellent book *Science, Evolution, and Creationism* published by the US National Academy of Sciences and Institute of Medicine asserts ‘The ideas offered by intelligent design creationists are not the products of scientific reasoning. Discussing these ideas in science classes would not be appropriate given their lack of scientific support’ (National Academy of Sciences and Institute of Medicine 2008, p. 52).

However, just because something lacks scientific support doesn’t seem a sufficient reason to omit it from a science lesson. This is a point that holds more widely than with respect to the teaching of evolution; for instance, when teaching about climate change, one might want to examine the argument that sunspot cycles are sufficient to explain all of global warming, even though this is no longer a reputable scientific position. Nancy Brickhouse and Will Letts (1998) have argued that one of the central problems in science education is that science is often taught ‘dogmatically’. With particular reference to creationism, they write:

> Should student beliefs about creationism be addressed in the science curriculum? Is the dictum stated in the California’s *Science Frameworks* (California Department of Education 1990) that any student who brings up the matter of creationism is to be referred to a family member of member of the clergy a reasonable policy? We think not. Although we do not believe that what people call ‘creationist science’ is good science (nor do scientists), to place a gag order on teachers about the subject entirely seems counterproductive. Particularly in parts of the country where there are significant numbers of conservative religious people, ignoring students’ views about creationism because they do not qualify as good science is insensitive at best. (Brickhouse and Letts 1998, p. 227)

51.6.4 Evolution in Science Museums

Education about evolution does not only take place in schools. It takes place through books, magazines, TV, the Internet, radio and science museums. Science museums have long had exhibits about evolution. Tony Bennett (2004) provides an historical analysis to look at how science museums have presented evolution. He attempts to discern the modes of power that lie behind the manifestations of particular forms of knowledge and concludes that

> In their assembly of objects in newly historicised relations of continuity and difference, evolutionary museums not only made new pasts visible; they also enrolled those pasts by mobilising objects – skulls, skeletons, pots, shards, fossils, stuffed birds and animals – for distinctive social and civic purposes. (Bennett 2004, p. 189)

In one sense this is hardly surprising – museums have to make selections about what to display and how to curate such displays, and these are clearly cultural decisions, whether one is referring to evolution or anything else. However, visitors to science museums can easily presume that they are being presented with objective fact. For example, the classic story about the evolution of the modern horse can be oversimplified to the point that the viewer concludes that evolution is linear and progressive.

Monique Scott too has produced a book about evolution in museums (Scott 2007) though her work, unlike Bennett's, is more to do with the present than with history. Using questionnaires and interviews, Scott gathered the views of nearly 500 visitors at the Natural History Museum in London, the Horniman Museum in London, the National Museum of Kenya in Nairobi and the American Museum of Natural History in New York. Perhaps her key finding is that many of the visitors interpreted the human evolution exhibitions as providing a linear narrative of progress from African prehistory to a European present. As she puts it:

> Despite the distinctive characters of each of the four museums considered here and the specific cultural differences among their audiences, it is clear that museums and their visitors traffic in common anthropological logic – namely the color-coded yardstick of evolutionary progress. In fact, visitors equipped with a weighty set of popular images – imagery derived from such things as *Condé Nast Traveler* magazines, *Planet of the Apes* films, and *National Geographic* images – occupy the nexus between the evolutionary folklore circulating outside the museum and that which has been generated within it. This collection of images often urges Western museum visitors to negotiate between the "people who stayed behind" and their own fully evolved selves (defined often by such culturally coded "evolutionary leaps" as clean-shaven-ness and white skin). (Scott 2007, p. 148)

So how might one hope that science museums would treat religion when putting together exhibitions about evolution? Museums have a number of advantages over classroom teachers; for one thing, they usually have longer to prepare their teaching. So we might hope that a science museum, while not giving the impression that the occurrence of evolution is scientifically controversial today, might convey something of the history of the theory of evolution. This would include the fact that evolution was once scientifically controversial and that religious believers have varied greatly as to how they have reacted to the theory of evolution. On the one hand we have today's creationists; on the other we have Charles Kingsley, the Anglican divine and friend of Charles Darwin, who read a prepublication copy of *On the Origin of Species* and wrote to Darwin:

> I have gradually learnt to see that it is just as noble a conception of Deity, to believe that he created primal forms capable of self development into all forms needful pro tempore & pro loco, as to believe that He required a fresh act of intervention to supply the lacunas w^{h}. he himself had made. (Kingsley 1859)

51.7 The Uses to Which Advances in Scientific Knowledge May Be Put

The tremendous growth in scientific knowledge means that we are faced with an ever-increasing number of ethical questions that our predecessors simply did not have to consider. Many of these are in the area of bioethics (e.g. Brierley et al. in press; Mepham 2008). How do we weigh human interests against those of the natural environment and laboratory animals? Is it acceptable to experiment on human embryos? And what role does religion have in answering such ethical questions about our use of scientific knowledge?

In a recent book titled *Dishonest to God: On keeping God out of politics*, Mary Warnock (2010), despite having a certain affection and sympathy for the Church of England, lists many examples where religious arguments have in her view inappropriately been used in parliamentary debates in attempts, some successful, some unsuccessful, to influence national legislation. She concludes:

> The danger of religion, any religion, lies in its claim to absolute immutable moral knowledge which, if justified, would indeed give its adherents a special place in instructing others how to behave, perhaps even a right to do so. (Warnock 2010, p. 165)

Our concern here is not so much with claims to knowledge as with how one makes practical decisions about scientific matters in a world with a multiplicity of values, religious and otherwise. And here religion has a place at the table (Reiss 2012). In just the same way as consequentialists have to learn to accept that many deontologists are not going to accept the consequentialist understanding of ethics as being decisive, and vice versa, so those of no religious persuasion need to accept that significant numbers of people have religious beliefs and hold that these beliefs help shape what is deemed morally right and morally wrong.

In this sense, those of no religious persuasion need to take the same sort of account of religious believers as those who eat meat need to take account of vegetarians. We would deem it unacceptable, nowadays, for the authorities in charge of a prison, a hospital or any other residential establishment to fail to provide vegetarian food on the grounds that vegetarianism is unnecessary, a minority lifestyle choice or a fad. In the same way, a secular society that respects its citizens needs to take account of religious views. Of course, precisely the converse holds too. A theocracy that respects its citizens needs to take account of the views of those who have no religious faith or belong to a minority faith.

I am well aware that to many with a religious faith, this may seem like ‘selling out’. To this objection I would respond as follows. First, it is as good as you are going to get nowadays in an increasing number of countries. Secondly, if a religious viewpoint has sufficient validity, it should be capable of holding its own in arguments with those who have no religious faith. For example, while Roman Catholic arguments about the unacceptability of contraception are very difficult to defend to non-Roman Catholics, more broad-based arguments about the sanctity of human life and therefore the unacceptability of euthanasia can receive a more sympathetic hearing among a secular audience so long as ‘the sanctity of human life’ is not seen as a trump card but is translated into religiously neutral language about respect and the protection of the vulnerable. Thirdly, my own reading of the Christian scriptures is that God’s nature is such that there is rarely an easily discerned voice from heaven. Usually, determination of what is morally right and morally wrong, while influenced by the reading of scripture and an understanding of the religious tradition to which one belongs, needs supplanting by broader reflection and study and should be informed, in the case of bioethics, by ongoing advances in the biosciences.

One objection to the line I have been advancing is that it is a relativistic one that depends on the specifics of history and geography. This is a common objection – not just in theology and bioethics but in other disciplines including science and aesthetics – and a standard response is to assert that to deny immutable knowledge is not necessarily to slide inexorably into relativism. One can occupy a middle ground. Indeed, as Parfit (2011) concludes, there are considerable commonalities between the main secular ethical frameworks (Kantian deontology, consequentialism and contractualism) once one gets down to specifics.

There will be some, who may or may not be atheists, who are not convinced that religion has any role to play in bioethics or any other issue to do with the use to which scientific knowledge is put. Religion, it might be maintained, rests on irrational belief in the supernatural and an excessive reliance on tradition, and while notions of respect may require us to tolerate such views, nothing should be done that might allow them to influence public policy. It is fine for people to have freedom of expression (e.g. freedom to attend worship) but that is entirely separate from granting religion a public role. If religion were to enjoy such privileges, we would have to extend them to other odd belief systems, such as those who believe they have been abducted by aliens (Clancy 2005) or those who hold that Elvis Presley is still alive (e.g. Brewer-Giorgio 1988, Elvis Is Alive 2012).

There are several reasons why this line of argument does not work. First, the proportion of the population, even in more secular countries, who have some religious beliefs, is considerably higher than the proportion of the population who believe in alien abductions or Elvis' longevity. Secondly, religious faith has been around for all of human time, whereas conspiracy theories and fads come and go. Thirdly, religious beliefs are often core to a person's being in a way that alien abduction (however upsetting) and Presley mania are but rarely. Fourthly, there is a close connection between many bioethical issues and religious faith which there isn't between bioethical issues and alien abduction or Elvis Presley. Of course, if the state were to set up a publicly funded museum about aliens, then there might well be a case for granting a voice to those who believe they have experienced such abductions (and this would almost certainly be good for business).

51.8 The Approach of Worldviews

Before going on to consider the pedagogical implications of all this, mention should be made of one approach to the science-religion issue that has become prominent within science education and is of considerable pedagogical value – namely, the concept of worldviews. The essence of a worldview, as the word itself implies, is that it is a way of conceiving and understanding the world that one inhabits (cf. Aerts et al. 1994). So, someone with a traditional Christian worldview is likely to believe that the world is fundamentally good but has become corrupted as a result of human sin. However, there is always the hope of redemption, and one of the tasks of Christians is to live their lives so as to help bring about the kingdom of God. On the other hand, someone with an atheistic worldview is likely to believe that the world is morally neutral and that there are no ultimate purposes in life beyond those that we decide for ourselves. Which of these two worldviews one finds the more convincing and conducive says much about oneself.

Creationism can profitably be seen not as a simple misconception that careful science teaching can correct, as careful science teaching might hope to persuade a student that an object continues at uniform velocity unless acted on by a net force, or that most of the mass of a plant comes from air as opposed to the soil. Rather, a student who believes in creationism can be seen as inhabiting a non-scientific worldview, a very different way of seeing the world compared to the scientific perspective. The pedagogical significance of this comes largely from the observation that one very rarely changes one's worldview as a result of one or two lessons, however well taught, whereas one may indeed replace a misconception with its scientifically validated alternative about such a brief teaching sequence (Reiss 2008b).

The probable reason for this difference in the difficulty of replacing worldviews and misconceptions is twofold. First, a student is likely to have far more of personal significance invested in a religious worldview than a scientific misconception. It is clear that the personal implications of abandoning a belief in a literal reading of the chronology of *Genesis*, including the 6 days of creation as 6 periods each of 24 h, are far greater than of discarding a presumption that plants gain most of their mass from the soil. Secondly, many scientific misconceptions are relatively discrete – one can discard one without this affecting much else of one's scientific understanding. Abandoning creationism entails accepting the notion of Deep Time, the relatedness of all life and the realisation that there is no *scala naturae*.

51.9 Pedagogical Implications

The question of the significance of religious issues for science education can be considered at the intended, the implemented and the attained curriculum levels (Robitaille and Dirks 1982). In a school setting there are therefore implications for curriculum developers, for classroom teachers and for learners. In this section I concentrate on teachers (whether in school science classrooms or informal settings) and learners.

Science teaching is demanding for teachers, particularly in a school setting. I have discussed elsewhere whether or not it is realistic to expect science teachers to deal with ethical issues in science lessons (Reiss 1999). Although there are examples of this happening successfully (Jones et al. 2010; Reiss 2008c), this is far from always being the case. It seems even more optimistic to expect science teachers to deal with religious issues, even when these are restricted to religious issues that relate to science. I therefore welcome the current guidelines in England about dealing with creationism in science lessons (DCSF 2007) which do not require but do allow science teachers to deal with the creationism and suggest that this principle be followed when dealing with religious issues in general in science classrooms.

The aim of including religion in science learning is not primarily to teach about religion but to enable richer and more effective ways to enable students to understand certain ideas within science and to help them appreciate better certain topics where science and religion interact. If science teachers, or other communicators of science, do deal with religious issues, or science issues that have religious connotations, I recommend that they be both true to science and respectful of their students and others, irrespective of such people's religious beliefs. Indeed, nothing pedagogically is to be gained by denigrating or ridiculing students.

The principle of respect for students has implications for assessment too. Well-designed examination material should be able to test student knowledge of science and its methods without expecting students to have to convert, or pretend that they have converted, to a materialistic set of beliefs. So, for example, while it is appropriate to ask students to explain how the standard neo-Darwinian theory of evolution attempts to account for today's biodiversity, it is not appropriate to ask students to explain how the geological sciences prove that the Earth is billions of years old.

Perhaps the most important implications of religion in general and Christianity in particular for the teaching of science come when teaching about the nature of science (Black et al. 2007). It can be a useful exercise with some students for science educators to get them to consider whether such topics as astrology, ghosts, paranormal phenomena and miracles fall within the scope of science or not. The aim is not to smuggle such topics into science but to get students more rigorously to think about what science is and how it proceeds. I remember one student of mine who undertook a survey among her peers to see whether, as predicted by astrology, their astrological birth sign was related to their personality, using a validated measure of personality. It wasn't. That student learnt something about science that was of value to her that I suspect she might not have learnt had I told her not to be silly and instead research something within mainstream science.

Skehan and Nelson (2000) point out that science educators generally do not do a good job of providing students with criteria to compare the strength of great scientific ideas. They emphasise the value of enabling students to develop skills of critical thinking when considering controversial topics such as evolution and provide a valuable list of eight criteria for comparing major scientific theories:

1. How many lines of independent evidence support the theory?
2. How many previously unconnected areas of knowledge did a theory tie together?
3. Does the theory make precise predictions?
4. How clear are the causal mechanisms?
5. Does the theory adequately explain the ultimate origin of the systems it describes and explains?
6. Is the theory scientifically controversial, or only publicly or politically controversial?
7. Is the theory fundamental to many practical benefits embraced by our economic system?
8. Is the theory widely understood and accepted by the general public?

This list differs considerably from the criteria discussed earlier (Sect. 51.3). Nevertheless, there would seem to be much of value in encouraging students to consider such questions (or others) when examining the validity of evolution or other major scientific theories.

Stolberg and Teece (2011) write about how to teach the science-religion issue but address their advice to specialist teachers of religion, not science, which provides a useful counterweight to the rest of this section. They point out that religious education teachers often assume that they should be neutral when teaching about controversial issues, yet this can be unrealistic and may not be the most effective way of teaching:

> Teachers may well feel that adopting a neutral stance – focusing on ‘the facts’, giving a ‘balanced’ picture – is most likely to be the ‘safest’ one to adopt. In practice, this is a very difficult strategy to achieve. The choice of facts you present (or withhold), the ‘expert’ opinions you share with your students and all the other educational judgments – in terms of the resources chosen and time devoted to the issue being explored – makes the effort of teaching religion and science issues in this way unrealistic. As with all controversial issues, however, your students need to be taught to examine critically the information they are given and the attitudes or values that have led to its production. So, rather than seeking to ‘not get involved’, you should be explicit about the aims and objectives of any exercise so that your students are aware of the circumstances in which they are being asked for their opinions and share the basis for their thinking. (p. 71)

51.9.1 Specific Issues to Do with Creationism

Part of the purpose of school science lessons is to introduce students to the main conclusions of science – and the theory of evolution is one of science’s main conclusions. For this reason, school biology and earth science lessons should present students with the scientific consensus about evolution, and parents should not have the right to withdraw their children from such lessons. At the same time, science teachers should be respectful of any students who do not accept the theory of evolution for religious (or any other) reasons.

Science teachers should not to get into theological discussions, for example, about the interpretation of scripture. They should stick to the science, and if they are fortunate enough to have one or more students who are articulate and able to present any of the various creationist arguments against the scientific evidence for evolution (e.g. that the theory of evolution contradicts the second law of thermodynamics, that radioactive dating techniques make unwarranted assumptions about the constancy of decay rates, that evolution from inorganic precursors is impossible in the same way that modern science disproved theories of spontaneous generation), they should use their contributions to get the rest of the group to think rigorously and critically about such arguments and the standard accounts of the evidence for evolution.

My own experience of teaching the theory of evolution for some 30 years to school students, undergraduate biologists, trainee science teachers, members of the general public and others is that people who do not accept the theory of evolution for religious reasons are most unlikely to change their views as a result of one or two lessons on the topic, and others have concluded similarly (e.g. Long 2011). However, that is no reason not to teach the theory of evolution to such people. One can gain a better understanding of something without necessarily accepting it. Furthermore, recent work suggests that careful and respectful teaching about evolution can indeed make students who initially reject evolution considerably more likely to accept at least some aspects of the theory of evolution (Winslow et al. 2011).

For sites of informal education, there are some issues that are the same for schools and some that are different. The principles of respect for students and others, irrespective of their religious beliefs, hold in the same way, but the principle of being true to science manifests itself somewhat differently depending on the nature of the site of informal education. If the site is one that identifies itself as being scientific, for example, a science or natural history museum or centre, then it can validly attempt to convince visitors that the standard scientific position is correct. Other informal education sites may have less of a science agenda. In any event, any museum or other site of informal learning should be able to prepare carefully and access resources in a way that may not be possible for a classroom teacher, so as to ensure that an exhibition, a display, a taught session or an outreach activity does deal with relevant religious issues.

Finally, there are an increasing number of creationist museums (e.g. http://creationmuseum.org/) and zoos (e.g. www.noahsarkzoofarm.co.uk/). Perhaps somewhat optimistically, I would ask those running such creationist places of learning to make one concession to evolution. I do not expect them to promote evolution, but it is reasonable to ask them to make it clear that the scientific consensus is that the theory of evolution and not creationism is the best available explanation for the history and diversity of life. It is perfectly acceptable for those running creationist institutions to critique evolution and to try to persuade those visiting such institutions that the standard evolutionary account is wrong. But just as science teachers with no religious faith should respect students who have creationist views, so creationists should not misrepresent creationism as being in the scientific mainstream. It is not.

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Chapter 52
Rejecting Materialism: Responses to Modern Science in the Muslim Middle East

Taner Edis and Saouma BouJaoude

52.1 Islam, Science, and "Materialism"

Contemporary Islamic responses to science are similar to responses from within other world religions – they exhibit a degree of ambivalence. Supernatural agents no longer play any explanatory role in the natural sciences, which challenges religious perceptions of divine design in the universe (Edis 2002). At the same time, modern science is closely coupled with technological prowess, making science appear indispensable to Muslim populations seeking to avoid commercial and military subordination in postcolonial times. This puts pressure on religious thinkers to try to achieve harmony between science and Islam while guarding against the materialist influences they perceive in the conceptual frameworks of Western science.

Since Islam is a diverse religion, and since Muslims constantly dispute what is the best interpretation of their religious tradition, there are always various competing visions about how to attain harmony. Some general descriptions are nonetheless possible.

Most popular versions of Islam harbor some ideas about harmony between science and religion, even though these ideas tend to be very superficial. Muslim populations worldwide sustain some very popular pseudoscientific beliefs (Edis 2007; Guessoum 2008). More complex interpretations of religious doctrines are readily available in more intellectual circles, but the level of engagement with science in

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more sophisticated theologies varies greatly. Most religious preoccupations, such as those about matters of social morality, have little to do with science, and in turn, most routine science does not touch on religion. But some scientific claims associated with the more ambitious theories of modern physics and biology invite friction with traditional beliefs about the supernatural governance of nature. Evolution in particular is a perennial source of conflict (Edis 2007).

Especially in the popular literature, "materialism" has become a common negative term expressing discomfort with modern ideas that emphasize impersonal, purposeless processes in explanations of phenomena. Historically, this is rooted in responses to mechanically inspired nineteenth-century materialist philosophy (e.g., Büchner 1884), together with later opposition to Marxist notions of materialism in the realm of social thought. Current developments of philosophical materialism, such as physicalism (Melnyk 2003), would naturally also be deemed unacceptable, due to their exclusion of supernatural agency and divine design. In popular writings, however, "materialism" is usually a generic term of abuse with little specificity. Nonetheless, as an umbrella term encompassing rejection of visible supernatural agency, opposition to "materialism" captures a central theme in Muslim concerns about modern science.

None of this is distinctively Muslim. Similar pictures can be drawn of Christian, Jewish, and even Hindu responses to theories such as evolution (Brown 2012). And when going beyond broad generalizations, it is very hard to identify a common, coherent Islamic philosophical framework through which Muslims tend to approach science. There is, perhaps, a distinctly Islamic preoccupation with questions about occasionalism and natural causality in Muslim thinking about science, reflecting the particular philosophical heritage of Islamic thought (Fakhry 2004; Leaman 2002). But such features of an Islamic philosophy of science are of minor importance. Both Islam and modern science are too varied for any common framework to dominate in Muslim thinking about science.

Instead, the distinctive aspects of present Muslim responses to science derive from the *history* of Muslim lands, especially the Middle Eastern heartlands of Islam. For Western Christendom, modern science, however revolutionary, still emerged as an organic development within its intellectual culture. When science caused religious discomfort, it did so as an endogenous heresy. For Muslim societies, modern science has been a Western import, significantly detached from their own intellectual tradition, including the highly developed medieval science of Islamicate societies. And for those Muslim thinkers most concerned about developing a religious response to modernity, modern science has often appeared as something to assimilate, to Islamize, and to guard against when it appears to challenge traditionally religious perceptions of nature (Edis 2007).

52.2 Medieval Islam and Modern Science

Natural science and doctrinally traditional forms of Islam have an uneasy relationship today. Muslim countries devote few resources to natural science, and the Muslim contribution to research in natural sciences such as physics is negligible

(Hoodbhoy 2007). Even in applied science and engineering, where the picture is not as dismal, Muslim countries suffer from relative backwardness. While Muslim populations have usually been enthusiastic about adopting modern technology, sustained creativity regarding new technologies still tends to characterize advanced Western and East Asian economies.

Muslims did not always have to play catch-up. Islamic empires famously were home to the best of medieval science. Though participation in serious intellectual life was inevitably confined to a small elite, Muslim scholars typically enjoyed better intellectual resources compared to their medieval European counterparts. Whether in medicine and public health, astronomy, optics, mathematics, or philosophy in the Greek tradition, Muslims were at the forefront of intellectual life. Historians of science continue to address the puzzle of why Europe became the site of the modern scientific revolution, rather than China or the lands of Islam (Huff 2003).

There are many myths about medieval Islamic science. Western observers used to describe Muslim scholarship as merely transmitting the heritage of Greek and Roman antiquity. This is not correct: Muslims further developed the ideas they inherited. Muslim science is often described as stagnating. Some Muslim reformers today add that this was due to the suppression of rationalist theologies, such as that of the Mutazila, and the influence of religious conservatives, such as al-Ghazali, who argued against philosophy (Hoodbhoy 1991). Yet those “foreign sciences” that were perceived as having practical utility were decoupled from the Greek philosophical tradition and continued to slowly develop even when philosophy faced a hostile climate.

Nevertheless, a large scientific and technological gap did open up between Europe and Muslim empires such as the Ottomans, Iran, and Mughal India. Europe made spectacular advances while Muslim conceptions of science remained closely anchored in the medieval tradition. With hindsight, it is easy to admire the accomplishments of medieval Muslim science. But this science operated within a premodern conceptual framework. Muslim medicine, for example, could boast interesting surgical techniques and impressive provisions for public health and hospital complexes. At the same time, the medical texts Muslims used were also full of bloodletting, humor theory, religious and magical practices, and no end of ideas that have a closer affinity to occult thinking than what became natural science as understood today. Furthermore, the medieval natural philosophy practiced in Islamicate societies, like its Catholic European counterpart, did not develop explanations within the sorts of theoretical framework comparable to, for example, early modern physics. Science remained an activity of collecting mostly isolated facts, and these facts were liberally mixed with what later scientists would come to call superstition. In this regard, modern science is radically different compared to its medieval precursors, in terms of explanatory power as well as its more immediately visible technological applications (Edis 2007). When Europeans, by historical accident, stumbled upon the new ways of thinking about nature that became modern science, Muslims would be left behind (Huff 2003).

Muslim intellectuals first became conscious of lagging in their knowledge of nature as a result of persistent military defeats of Muslim empires. The Ottoman Empire, which was nominally sovereign over today’s Turkey and most Arab countries up until the twentieth century, was closest to Europe. And in the seventeenth century dire reversals in the Ottoman-controlled Balkan territories forced Ottoman intellectuals to ask why the conquering armies of the faithful were suddenly so weak. Scholars called for intellectual and institutional renewal among Muslims. These calls gathered strength as it became clear that science-based technology and modern forms of social organization gave the Europeans their advantage. Similar experiences were to follow for Mughal India, Iran, and Indonesia – all but the most isolated Muslim countries. Muslims everywhere would face a similar challenge from the industrialized West, and Ottoman intellectuals would craft responses that would find echoes across the Muslim world.

52.3 Ottomans Respond to Modern Europe

Confronted with western European military and commercial superiority, Ottoman intellectuals became preoccupied with rescuing the Empire. Many insisted that if only Muslims would redouble their commitment to faith and proper observation of divine laws, Islam would be restored to its proper dominance. But most, including most religious scholars, came to recognize that technology was the key to European power and that Muslims would have to acquire and master the new forms of knowledge. How this was to be best accomplished, and especially how the religious nature of Muslim civilization could be protected, became matters of contention (İhsanoğlu 2004). This debate shaped intellectual life in the last century of the Ottoman Empire, spilled over into successor states such as the Republic of Turkey and Egypt, and continues vigorously to the present day. Indeed, many of the themes running through earlier Muslim ideas about renewal remain at the forefront of debates today.

In the seventeenth century, Ottoman intellectuals such as Katib Çelebi argued that Muslims needed to be more open to foreign scientific knowledge (Demir 2001, pp. 48–52; Lewis 1993, Chap. 16). Obviously, Western Europe could no longer be ignored; Muslims needed to learn as much as possible about European technical accomplishments. Ottoman officialdom would adapt, for example, sending representatives to European capitals rather than relying only on European diplomats stationed in Istanbul. By the early nineteenth century, as the Ottoman Empire's European territories continued to shrink, diplomats, travelers, and students became a significant conduit of information about Western ways. Translations of Western technological and scientific works became available, and westernized forms of education attracted the children of elites.

Together with Western Europe, however, Ottoman Muslims also looked toward their own history. Especially before the nineteenth century, almost all intellectuals were grounded in the classical tradition of religious scholarship. And for religious scholars, reforming Muslim attitudes toward knowledge made sense in the context of reviving the specifically Muslim "religious sciences." Even Katib Çelebi had expressed a perception that Muslims had become "imitators," relying too much on precedents set by earlier scholars. Assimilating the foreign sciences could be best accomplished if all the Muslim sciences were to become more vibrant. After all, the story went, in their glory days Muslims had enjoyed the best of the foreign sciences, anchored to a God-centered perception of nature, all mediated by a devout engagement with the sacred sources.

Achieving scientific progress in the context of a revival of religious scholarship remains a prominent theme in doctrinally conservative Muslim discourse today (Edis 2007). But the more general notion of revival resonates among more liberal parties to the debate as well. Liberals call for reviving rationalist currents of theology and accuse conservatives of preventing vital social and technological changes (e.g., Mernissi 1992). Most parties agree that recovering the intellectual practices that led to the golden age of medieval Muslim science is vital. Almost everyone overlooks the enormous differences between medieval and modern science.

Calls for revival aside, the immediate task faced in the crumbling Ottoman Empire was to transfer European technology and acquire modern organizational skills. Religious intellectuals felt a need to reconcile this dependence on Europe with the superiority due to Islam. İbrahim Müteferrika, a Hungarian convert to Islam responsible for the first Muslim-operated Ottoman printing press in 1727, stated that Europeans had advanced in rational science precisely because they needed to compensate for the inferiority of their religion. In social and religious matters, Islam was unquestionably superior (Black 2001, p. 268). Religious scholars typically argued that it was permissible to learn the technical knowledge possessed by infidels in order to use this knowledge against them in a military confrontation. More generally, scholars agreed that borrowing knowledge was necessary to defend Islam. However, this borrowing would have to take place in such a way as to guard against cultural contamination.

These remain major themes today. Conservative Muslims often temper their enthusiasm for technology with a conviction of religious superiority and highlight the need to protect the core values of Islamic civilization while modernizing. Indeed, even very traditional religious communities can sometimes adapt quickly to a highly technological environment, strengthening their commitment to orthodoxy in the process (Blank 2001). But more traditional religious commitments remain in tension with institutional structures that are aimed toward contributions to progress within a global scientific enterprise, rather than mainly transferring existing technology.

Just what this protected core of Islam should be is also, naturally, open to dispute. The modernization of Muslim countries over the last few centuries has brought large-scale social changes, including the erosion of the power and social position of the class of religious scholars. In the nineteenth century, this opened up possibilities for more modernist interpretations of Islam (Alperen 2003). Jamal al-Din al-Afghani in Ottoman lands, Sayyid Ahmad Khan in British India, and later Muhammad Abduh in Egypt advocated an interpretation of Islam that was more open to modern education and argued that Islam was in its essence a scientific religion. They downplayed the more miraculous and magical elements in popular piety, joining traditional Sunni orthodoxy in their suspicion of Sufi enthusiasm.

Muslim modernism, however, also harbors a conservative impulse. For example, while modernists downplayed overtly supernatural aspects of popular piety, they did not challenge traditional views of the sacred sources. Modernists produced an apologetic response to modernity rather than a coherent endorsement of modern values. In the twentieth century, with increased literacy in Muslim populations, religious movements that emphasized individual access to sacred sources, bypassing the mediation of traditional scholarship, became more popular. Often this implied a more literal reading of sacred texts and a fundamentalist flavor of populism. Modernist themes of moving beyond traditional forms of religious scholarship are today endorsed by fundamentalists who feel at home in a globalized economy (Roy 2004), as well as by more liberal-minded religious thinkers.

Most doctrinally conservative Muslim responses to Western encroachment have included an element of cultural defensiveness. Nevertheless, westernizers and secular-oriented thinkers have also taken part in the debate. In the Ottoman Empire, such intellectuals were more often rooted in the military and imperial administration rather than in traditional religious scholarship. The Ottoman military went through a wrenching westernization in the late eighteenth and early nineteenth centuries, and some military intellectuals began to think that a more comprehensive westernization of Ottoman society was unavoidable if the Empire was to avoid annihilation in the hands of European powers. A small minority of thinkers educated in a European style even expressed secular ideas. The more radical westernizers finally got a chance to implement their agenda in the 1920s, with the Turkish Revolution founding a new republic in the Anatolian heartland of the Ottoman Empire.

Secular westernizers proposed to solve the problem of adopting Western science by forcing religion to become a private affair. While personally remaining Muslims, modern Turks would become as Westerners in public life, joining the enterprise of creating modern knowledge on equal terms with Europeans (Kazdağlı 2001). Commitment to such a comprehensive ideal of secularization did not take root beyond a relatively small social elite, but due to its command of state power in Turkey and influence on the elites of many other Muslim countries, a secular outlook was a major party to Muslim debates over science and religion in the twentieth century. Even today, when Islamist politics dominate the public imagination in the Muslim Middle East, a secular westernizing view retains some influence due to its overrepresentation among elites and in those scientific institutions established in Muslim countries.

Today, the Muslim world is in a period of extensive religious experimentation. The desire to achieve a distinctly Muslim way of being modern has produced many competing ideas. So modernism, hopes for revival, westernization, or cultural defense are not the only themes that surface in current controversies over science and Islam. For example, Sufism, the mystical strand of Islam, has met with disapproval from both westernizers and conservative scholars and thus has been greatly disadvantaged during the modernization process. Recently, a kind of neo-Sufism has begun to appeal to modern professionals in an urban environment, influencing debates over miracles or spiritual realities accessed through mysticism. Occult notions, then, can find support from those who want to revive medieval perceptions of nature, those who defend survivals of such beliefs in existing religious orders, but also from neo-Sufi's who bring a westernized, New Age flavor to the arguments (Edis 2007; Raudvere and Stenberg 2009).

Even with this diversity of themes, however, it is possible to make some generalizations about the recent history of responses to Western science in the Ottoman Empire and its successor states. Both among religiously conservative intellectuals and much of the general public, enthusiasm for technology has been combined with an insistence that religious convictions should remain at the center of how Muslims perceive nature. This brings up the potential of friction with modern science, which has tended to disenchant the world. Moreover, this friction usually surfaces in the context of institutional and social conflicts between more religiously oriented and westernized segments of Muslim populations.

52.4 Against Materialism

Centuries of military disadvantage taught the Ottomans and their successors that their problems could not be solved by immediate technology transfer or by better techniques of organization. As long as Muslims were borrowers rather than creators of practical knowledge, they would always lag behind.

Most Muslim countries have been considered "underdeveloped" during the twentieth century. Today, countries such as Turkey have attained a middle-income status in part due to industrial manufacturing enterprises migrating away from Europe, but they remain in a peripheral position in the global economy, especially where the cutting edge of science and technology is concerned. Therefore technologically, Muslim-majority countries typically remain in a position of playing catch-up. This means that as with the past century, their educational and industrial policies continue to emphasize immediate applications and technology transfer over basic science. In Turkey and the Arab Middle East, the institutional infrastructure for basic science is poor, and engineering programs typically attract more talented students than natural sciences such as physics. Moreover, an emphasis on applied science has been easy to reconcile with demands for cultural defense. Both in technologically advanced Western countries and among Muslims, the culture of engineering is notoriously more politically and religiously conservative compared to natural science (Gambetta and Herzog 2007). Engineers and medical doctors who reject evolution are commonplace but a rarity among physicists and biologists. And in Muslim countries, engineers are well known to be heavily represented in the leadership of political Islamist movements. But relative success in adopting foreign technologies cannot solve the deeper problem: Muslim populations still lag in the creation of new knowledge, even when restricted to immediate practical knowledge.

This puts pressure on Muslims to master natural science, not just applied science and engineering. Religious responses to natural science, therefore, become important, particularly in areas where modern science appears to challenge traditional beliefs.

In the nineteenth century, most Muslim thinkers continued to take it for granted that Islam was religiously superior to the superficial Christianity of urban Western Europe. Some travelers and diplomats greatly admired Europe, adopting a “the West is the best” mentality. But many Muslim observers of Europe described lands that harnessed vast power through industrialization but were also moral disaster zones. Europeans cared about material things, were good at achieving worldly power and wealth for their elites, but were spiritually lacking. In the twentieth century, visible secularization in Europe would further bolster perceptions that Christian piety was inadequate compared to Muslim faith (Aydın 2000, pp. 43–50). In any case, the European example only intensified concerns that acquiring new knowledge should be done with care to avoid cultural contamination. Yet it was also clear that creating new knowledge required new intellectual habits and adopting those new ways of perceiving nature that were ushered in by the new natural sciences. Culture could not remain immune to change.

Ottoman perceptions of the natural science they imported were colored by the institutional struggle of European science to become independent of religion. Conflict with church authority was not a concern; even today, religious thinkers proudly declare that Islam has no ecclesiastical structure that can impede scientific inquiry (Aydın 2000, p. 86; Şahin 2001, pp. 177–182). But especially in the nineteenth century, materialist currents in European intellectual life influenced Muslim perceptions of science (Gümüşo lu 2012). Popular materialists such as Ludwig Büchner not only publicly argued against supernatural realities – unthinkable in a Muslim environment – they made it clear that their philosophy was inspired by scientific developments (Büchner 1884). Furthermore, materialism also had radical political implications, even before Marxism developed a significant following. When Darwinian evolution appeared on the intellectual scene, it immediately became part of the larger Western debate over science and the supernatural, rather than just a theory of interest to biologists.

European materialist literature aimed at a middle-class market also attracted attention from Ottoman elites in intellectual centers such as Istanbul and Egypt. Official censorship would not allow the full extent of materialist skepticism about the supernatural to become public, but large portions of books by materialist and anticlerical figures such as Ludwig Büchner, Ernst Haeckel, and Andrew Dickson White were translated and sold reasonably well. Darwinian evolution briefly became a matter of debate. Ottoman elites were in no position to contribute to scientific research, but many desired to learn about science, and in the late nineteenth century, popular science imported from Europe included a dose of materialism (Özervarlı 2003; Ziadat 1986, p. 23).

The direct influence of those Ottoman intellectuals who took a positive view of materialist ideas never extended beyond a small elite. Nevertheless, materialism took a symbolic role in debates over the role of religion and the power of the class of religious scholars in the changing empire. The handful of Ottoman materialists may have been a negligible extreme, but they were not the only ones who suspected Muslim lands were held back by religious obscurantism. And since materialism was a blatant example of infidelity, for conservatives the blasphemy materialists fell into could also serve as a warning against imitating Western ways blindly. Indeed, since conservative Muslims already held Europe in suspicion as a spiritually inferior civilization given to materialism in a crass sense, it seemed that a depraved denial of all that was godly was a logical endpoint of the Western approach to knowledge. Denouncing a symbolic "materialism" could serve as part of a warning against westernizing so far as to lose a Muslim identity. Even today, some Turkish conservatives remember the nineteenth century as a time when a materialist threat first surfaced and demanded a vigorous response from the faithful (Akyol 2009; Hanioğlu 2008; Gümüşoğlu 2012).

Early twentieth-century reform-minded scholars, such as Said Nursi in Turkey, developed apologetic responses to nineteenth-century materialism. Nursi attacked ideas such as natural causality and evolution, while at the same time endorsing science as a way of understanding God's creation. Today, a vaguely defined materialism remains a symbolic enemy, especially for many conservative Muslims – even though, especially after the waning of Marxism, explicitly materialist points of view do not have a significant presence in public debates. The path to reconciling science and religion still goes through defending against a threat of materialism.

52.5 Making Science Acceptable

Some Muslims have sometimes had moral objections to an application of science (Sardar 1984). This is, however, very different from rejecting a "fact" discovered by scientists. Indeed, conservative Muslims have typically been comfortable with science as a means of making an extensive catalogue of facts, presumably documenting the glories of God's creation.

Modern science potentially causes trouble, not because of any result produced in a laboratory but because it is *not* a catalogue of facts collected like stamps. Mature sciences such as physics and biology gain much of their power from the compelling conceptual frameworks they establish, explaining a very wide range of phenomena. Classical physics, later corrected and expanded into modern physics with relativity and quantum mechanics, are ambitious attempts to capture the fundamentals of how the world works. Darwinian evolution claims to present and explain a pattern of descent common to all of life. In such conceptual frameworks, supernatural agents are conspicuous by their absence. Moreover, important aspects of these frameworks are, at face value, hard to reconcile with traditional religious beliefs about how God must have a role in our understanding of nature. Quantum randomness challenges the notion that the universe is controlled by a divine purpose that is distinguishable from chance. Darwinian evolution does not just contradict Quranic stories about the special creation of Adam and Eve; it undercuts the common religious intuition that creativity must always be due to an overarching intelligence rather than a product of mindless processes (Edis 2002, 2006).

Western Christians have responded to such challenges not just by fundamentalist resistance but also by liberal reinterpretations of theology. But from a conservative

Muslim perspective, liberal theology can easily look like capitulation to materialism – another illustration of how Europeans have been unable to defend the core religious truths revealed in the Abrahamic faiths (Aydın 2000, p. 61). Moreover, science is not just a source of worry for intellectuals debating abstract matters. Most ordinary Muslims, even in technologically relatively modern environments, continue to understand their faith in a context where divine action directly and immediately shapes the world. Victims of an earthquake, for example, will usually interpret the earthquake as the will of God, very often as a divine punishment (Küçükcan and Köse 2000) – a view supported by Quranic stories about God punishing wayward peoples by earthquakes. As modern technology gives people more control over aspects of their lives, and state-mandated education includes a more scientific picture of nature, questions about science and religion take on a public significance beyond their merely intellectual interest.

The present Muslim debate over science and religion is significantly different compared to the debate taking place in advanced Western countries. Scientific institutions are weaker in Muslim lands. They are less able to assert their independence from cultural politics. Moreover, liberal theological options, which help grant science an independent sphere of operation, do not enjoy as strong a social presence. Indeed, observing the secularizing trajectory of Western societies, conservative Muslims are likely to be even warier about repeating the mistakes Christians have made.

Doctrinally conservative Muslims, then, often feel a need for an apologetic response to the ways modern science can engender skepticism about supernatural claims. Their literature on science and religion is broadly similar to Christian equivalents; after all, beyond a number of specific doctrinal matters, all Abrahamic faiths face similar challenges from the naturalistic tendencies within science. Like their Christian counterparts, conservative Muslims typically rhetorically endorse science and defend a perception of modern science in complete harmony with traditional beliefs. Where harmony is strained, however, making science acceptable requires some work. Especially in the popular apologetic literature, three approaches stand out: ignoring the challenge, co-opting science, and outright rejection.

Some questions that have become staples in the Western discussion over science and religion have little connection to the concerns of ordinary Muslims. Popular apologetics therefore tends to ignore them, and without public controversy, religious intellectuals devote little attention to such topics. Modern physics is rarely the subject of sustained reflection, with a few exceptions. Some thinkers try to validate the medieval Muslim philosophical position of occasionalism through quantum mechanics, though the typical result is a distortion of the physics. More often, quantum physics gets invoked in a neo-Sufi, even parapsychological context. This almost never rises above the level of popular pseudoscience (Edis 2007). A recent area of scientific development that has drawn the fire of Western opponents of materialism, such as the intelligent design movement, is cognitive neuroscience (e.g., Beauregard and O'Leary 2007). It is hard to find any distinctively Muslim response to the currently dominant materialist point of view in neuroscience.

Another common strategy, especially in popular apologetics, is to co-opt science, arguing that modern science supports traditional beliefs. For example, there is now an extensive literature that is very popular throughout the Muslim world, purporting to demonstrate how the Quran is full of miraculous anticipations of modern science and technology (e.g., Bucaille 1979; Nurbaki 1998). This parallels the way many conservative Protestants claim fulfilled prophesies as a way of providing concrete support for their belief that the Bible is the word of God. More sophisticated Muslim thinkers often have misgivings about this style of apologetics (Rehman 2003), but its popularity remains very strong.

Co-opting science extends to the way that some Muslims take a conciliatory attitude toward evolution, accepting an explicitly guided, non-Darwinian form of biological change. In this connection, there are occasional arguments that medieval Muslim scientists had already thought of the concept of evolution (Bayrakdar 1987). Much of the literature arguing that modern science supports traditional Islam is opportunistic. For example, while many conservative Muslims rely on various pseudobiological arguments to support traditional gender roles, some selectively quote from the popular sociobiological literature to that end while ignoring the evolutionary context of such arguments (Edis and Bix 2005).

Some scientific and scholarly ideas, however, appear to be both worthy of attention and too tainted with materialism to assimilate easily. One example is modern Quranic criticism, which is practiced almost exclusively outside of Muslim lands, and is nearly universally rejected by devout Muslims when they are aware of it. At least one European scholar has found it necessary to publish under a pseudonym to avoid repercussions (Luxenberg 2000). In natural science, the clearest example is Darwinian evolution.

Darwinian evolution – that is, a completely naturalistic understanding of common descent as driven by purposeless material processes such as variation and selection – has usually faced rejection from Muslim populations. Ideas about evolution first reached Ottoman intellectuals in the context of the European controversy about science versus revelation. And the first Ottoman defenders of Darwin came from among westernizers who were less interested in biology than evolution as an example of materialism triumphing over clerical obscurantism. Traditional religious scholars naturally reacted with condemnation. Interestingly, the prominent modernist Jamal al-Din al-Afghani also rejected evolution as an anti-religious philosophy that was absurd on the face of it. He only made concessions to a possibility of a non-Darwinian, guided version of evolution toward the end of his life (Keddie 1968, pp. 130–174; Bezirgan 1988).

As a result of the rejection of Darwin even by reformist Turks and Arabs keen to avoid the taint of materialism, the nineteenth-century Ottoman debate about evolution was stillborn. Most Middle Eastern Muslims, even many among educated elites, remained creationists by default. Indeed, until recently, Darwinian ideas usually did not have enough of a public presence to inspire an elaborate creationist pseudoscience as a reaction. As a result, conservative Muslim attitudes toward evolution today are often roughly comparable to those of more fundamentalist and Pentecostal Christians worldwide. Evolution is clearly unscriptural and obviously a materialist idea; therefore, it cannot be correct – nothing more need be said.

52.6 The Nur Movement

Muslim responses to materialist currents in science do not trickle down from academic theologians. They do not arise from traditional religious scholarship, which has little scope for analysis aside from condemning ideas that go against orthodox readings of the sacred sources. Muslim responses typically come from devout intellectuals facing immediate practical problems, and even more important, they achieve prominence if popular religious movements adopt them.

In this regard, the example of Said Nursi and the "Nur movement" he inspired is particularly important. Western scholarship on Islam has tended to be driven by political questions such as the potential for democracy in Muslim countries, and therefore figures such as the early modernists and later theorists of political Islam such as Sayyid Qutb and Abul A'la Maududi have drawn much attention. They all have writings that usefully represent aspects of modern Muslim thought on science, reason, and religion (Euben 1999). Nursi's movement, however, has been instrumental in shaping popular Turkish attitudes about science and religion today. It pioneered forms of popular apologetics that are now very common throughout the Muslim world. The Nur movement deserves more attention.

Nursi was trained as a traditional scholar in the Ottoman provinces and was most active in the first half of the twentieth century. Much of his thought repeats modernist themes, including an emphasis on reforming Muslim education, a positive view of technology, and a desire to combat harmful intellectual influences associated with nineteenth-century materialism. He argues that mystical illumination complements scientific investigation, that all useful arts and sciences emanate from the "names of God," and that the Quran anticipates modern technological possibilities (Abu Rabi' 2003).

None of these are remarkable ideas for Nursi's time and circumstances. But unlike many other reformist scholars, Nursi started a successful popular movement. He produced the *Epistles of Light*, revered by the Nur movement almost as a secondary scripture. After his death, Nur adherents continued to organize on the basis of studying the *Epistles*. The movement has been notable for its modernizing emphasis, capitalist mentality, and nontraditional forms of organization and religious authority structure. Social scientists have pointed to the Nur movement as an example of a very modern, pro-technology Islamic movement with a strong popular constituency. They have argued that it has been instrumental both in laying the groundwork for provincial economic development and in spearheading the success of modern Islamic forms of thinking in Turkey (Mardin 1989; Yavuz 2003).

The Nur movement is too large to be unified. Its many splinter groups today include the followers of Fethullah Gülen, one of the internationally best known Muslim leaders of recent times, plus others that enjoy considerable political influence in Turkey (Çalışlar and Çelik 2000). Yet a common denominator of Nur-inspired movements for decades has been a form of popular apologetics that places great emphasis on harmony between Islam and science. Most pseudoscience in Turkey, other than superficial Western-derived and media-driven fads such as astrology and UFOs, has the signature of the Nur movement.

In pre-Internet times, the Nur movement produced popular science magazines that regularly included articles on how Muslims should embrace technology and how the Quran miraculously anticipates modern developments, containing knowledge of astrophysics or embryology. They opposed evolution. The immediate social influence of the movement fluctuated according to changing political circumstances within Turkey, but over the long term, the Nur style of apologetics appealed beyond the study circles focused on the *Epistles of Light*. Today, some of the old popular science and religion magazines survive, but the Nur style of apologetics has acquired a much broader influence, becoming embedded in popular culture and spreading through new forms of media.

In today's Turkey, anyone with views on science and religion – for example, an academic theologian proposing a more liberal view concerning evolution – has to contend with the widespread influence of the Nur movement. The Nur version of harmony between science and Islam is entrenched not just in popular culture and popular pseudoscientific beliefs, but it also enjoys elite influence. Academic theologians and scientists who either have direct connections to the Nur movement or have absorbed its ethos are significant voices in the Turkish debate over science and religion (Şahin 2001; Tatlı 1992). Through such channels, opposition to evolution, for example, has a presence in the intellectual high culture as well as the mass media.

52.7 The Growth of Creationism in Turkey

Said Nursi was disappointed by the Turkish Revolution of the 1920s. The westernizers in control of the new Turkish Republic established official secularism, suppressing political expressions of Islam. Nursi spent time in prison. The intellectual influences upon political leaders such as Mustafa Kemal Atatürk tended to be secular, anticlerical, and even included then-current versions of materialism and positivism (Parla and Davison 2004). Science, not religion, was to light the path to a brighter future. Evolution entered the curriculum. Still, evolution remained a relatively small offense against religion in a state-controlled educational system that aimed to make religious sentiment a private matter rather than a reference for public policy.

Until the 1960s, like other Middle Eastern Muslim countries, Turkey presented a picture of grudging but gradual secularization. The Nur movement and similar religious conservative groups produced some creationist literature, but their market was limited. Anti-evolutionary activity stayed confined to the subculture of a strictly observant, self-consciously orthodox minority. It is harder to know what the bulk of the population thought of evolution in the textbooks, in the days before constant opinion polling. Most likely, evolution inspired passive resistance at most, when it drew attention at all.

In the 1970s, together with the rest of the Muslim world, a newer form of political Islam started to gain strength in Turkey. Evolution became a minor culture war item, a way for Islamists to demonstrate opposition to secularization without naming official secularism as a target. In parliament, an Islamist political party attacked the presence of evolution in education but produced only a minor media stir (Atay 2004, pp. 136–137).

Creationism came into its own in the aftermath of the conservative military dictatorship of 1980–1983. Religious conservatives, many with Nur movement connections, gained control of the Turkish Ministry of Education in the first quasi-civilian government. They were convinced that evolutionary ideas were morally corrosive, and yet they were very aware that science commanded significant cognitive authority. So they needed a way to show that evolution was a scientifically dubious idea, maybe even a fraud. They found the resources they needed in Protestant "scientific creationism." Adding an odd chapter to the history of Muslim intellectual borrowing from the West, religious conservatives invoked Christian creationists in a mirror image of the way secularists tend to rely on Western scientific authorities. While the Turkish creationists downplayed some important features of Protestant creationism such as a young earth and flood geology, they adopted the bulk of the anti-evolutionary debating points developed by their Christian counterparts. Indeed, the Ministry of Education had samples of "scientific creationist" literature officially translated and made available to high schools and teachers (Edis 1994).

Since this creationist breakthrough, Turkish secondary school textbooks have often contained anti-Darwinian or explicitly creationist material (Yalçınoğlu 2009). Islamists and conservatives favor a religious identity politics, so even though opposing evolution is not a leading item on political agendas, it tends to be a background commitment. Since 2002 a moderate Islamist party has held power. The Ministry of Education under its administration is perceived as sympathetic to creationism, due to incidents such as retaining creationist material in the curriculum in the face of academicians petitioning for the removal of unscientific material (Kotan 2006).

Islamist politics in Turkey relies on alliances between working class constituencies such as recent immigrants to large cities and a newly prosperous provincially based business class, often united by antagonism toward longer-established secular elites. Religious populists present political conflicts over religion as a clash between a debased, inauthentic secularism and the traditional piety of the common people. Nevertheless, the primary constituency for Turkish creationism is not traditionalists but modern believers, even though they are theologically conservative. It is precisely because they want to take their place in the modern world, where mastering technology is the key to success, that creationists fashion a pseudoscience that harmonizes science and their religious convictions.

Since 1997, the popular appeal of Turkish creationism has deepened. Indeed, the Turkish style of creationism has spread internationally, throughout other Muslim countries and the Muslim diaspora in Europe and North America. The central figure in this development is Harun Yahya, a pseudonym that serves as a brand name for a ubiquitous, well-funded, and media-intensive form of creationist propaganda (Edis 1999; Edis 2003; Riexinger 2008; Sayın and Kence 1999). There is not much new about the content of the Harun Yahya material: it consists of arguments that have no scientific substance and distortions of science often copied from Christian anti-evolution literature, presented with a conservative Muslim emphasis. The range and production quality of this material, however, is impressive. Creationism in the Turkish Ministry of Education resulted mainly in some translations and a few paragraphs expressing opposition to Darwinian evolution in some otherwise unremarkable textbooks. The Yahya operation is much better suited to a postmodern media environment. Large numbers of glossy books, magazines, videos, websites, public events, and television interviews make Yahya's simple, intuitively appealing creationism available to a large public. None of this material is marked out as being religious literature of interest only to a conservative Muslim subculture; from its presentation style to its use of everyday language, Harun Yahya material is designed to be marketed to ordinary, modern Muslims who need not be attracted to strictly observant varieties of Islam. Furthermore, Yahya material is artificially cheap and is often distributed free of cost. Clearly the Harun Yahya enterprise has considerable financial backing, though the source of these funds is not entirely clear.

Turkish scientists have tried to counter such popular creationism, but in the public arena, the creationists hold the upper hand. One reason for the weakness of the scientific position is that Turkish scientists not been able to present an organized response, in part due to other conflicts with the government due to neoliberal policies that would further weaken the position of basic science. In addition, there is also some opposition to evolution within Turkish academia, especially in newly established provincial universities. Even some biologists can go in search of an "alternative biology" more similar to intelligent design than Darwinian evolution (e.g., Yılmaz and Uzuno lu 1995). Moreover, scientists, especially in the more prestigious universities, represent a very westernized population. They have been most comfortable phrasing their opposition to creationism in the idiom of defending the secular nature of the Turkish state (Sayın and Kence 1999). Since republican secularism has been discredited in popular politics, this has been a strategic blunder.

Islamist rule may also have affected the structure of support for science in the Turkish state. In March of 2009, *Bilim ve Teknik*, the popular science and technology magazine published by the Scientific and Technological Research Council of Turkey, was supposed to have been released with a cover story about the two hundredth birthday of Darwin. A political appointee in upper management, an engineering Ph.D., intervened to change the cover story and delete the Darwinian material (Abbott 2009). This led to another round of the creation-evolution wars in the popular press. Religious columnists charged "Darwinists" and "materialists" with being the real censors, disallowing alternative scientific views favorable to creation from enjoying a proper hearing. Secularist writers interpreted the event as evidence of growing Islamist entrenchment in scientific institutions.

Building on its success in Turkey, the Harun Yahya brand of creationism has now gone global. Today, Yahya material is available in languages spoken by Muslim populations all over the world. Yahya books are prominently displayed in Islamic bookstores in London, appear in schools in Pakistan, and are promoted by speaking tours in Indonesia. As a publicity stunt, Yahya's publisher mailed copies of a volume of a typically lavishly produced encyclopedia called the *Atlas of Creation* to scientists and educators in Europe and North America, drawing media attention outside of Islamic circles (Yahya 2007). There is now a global variety of popular Islamic creationism that goes beyond long-standing but usually passive Muslim resistance to Darwinian ideas. Many modern Muslims are attracted to claims that evolution is scientifically false and that science, properly done, supports Quranic notions of special creation.

52.8 Accommodating Evolution

Strict creationism, whether based on outright rejection of science that contradicts conservative readings of the sacred sources or expressed in the form of a Harun Yahya-style pseudoscience, is not the only option available to Muslims. A minority consisting of theologically liberal and secular Muslims, for example, tends to accept evolution due to their general trust of modern education and science as a cognitive authority. Such acceptance of evolution need not imply more than a superficial knowledge either of biology or of the religious worries about evolution articulated by more conservative Muslims. Nevertheless, there is a constituency for efforts to interpret Islam in a way that is compatible with at least some minimal form of evolution.

The easiest option for harmonizing evolution and traditional beliefs is to downplay Darwinian explanations of the evolutionary process, affirming common descent while portraying biological evolution as a divinely guided progression toward higher forms of life (Ateş 1991). A particular concern is to interpret the Quran in such a way as to allow for a degree of evolution. Some theologians, for example, read 24:45 in the Quran, speaking of God creating all animals from water, as a statement that life emerged from the oceans, just as the scientific history of life on Earth has it. Verses that describe the special creation of Adam and Eve, however, need more strenuous attempts at reinterpretation. Very few Muslims will countenance the idea that the Quran is anything but the direct and unadulterated word of God. Therefore, while many Muslims think that considerable evolution under divine guidance may be applicable to nonhuman forms of life, devout believers typically consider humanity to be a separate creation.

Evolution can also become more acceptable if similar ideas can be located in a Muslim intellectual tradition. Some Turkish theologians have proposed reviving such ideas under a label of “evolutionary creation theory” (Altaytaş 2001; Bayrakdar 1987). This appears to be partly based on questionable readings of medieval philosophical reflections on the ancient Greek concept of the great chain of being. Still, in a cultural climate that privileges Islamic authenticity, such historical connections, even if forced, may help make guided evolution a more attractive view. In any case, efforts to compromise between Darwinian evolution and creationism are common. If the religious experimentation in the Muslim world today should lead to a liberalizing trend that can appeal to a broader base than a westernized elite, guided evolution will become an even more popular option.

Many influential Muslim intellectuals also avoid naive Quranic literalism and strict creationism while also expressing skepticism about the Darwinian, naturalistic form of evolution that is the established position in natural science. Some internationally known scholars defend such views. For example, Seyyed Hossein Nasr and Osman Bakar are well known for their outline and defense of a specifically Islamic philosophy of science. Both Bakar and Nasr allow for limited biological changes over time but deny that purely natural mechanisms can ever account for the creativity seen in the history of life. Like popular creationists, they describe evolutionary biology as a manifestation of materialist philosophy rather than a real science with a true empirical foundation. They go further, however, contrasting a Darwinian view of life with a God-centered perception of nature that hearkens back to classical Islamic conceptions of knowledge and creation. They aspire to restore the Islamic religious sciences to a position of preeminence and to have revelation provide the framework for all knowledge claims, including investigations of the natural world (Bakar 1987, 1999; Nasr 1989).

Proposals to "Islamize science" or otherwise reconstruct modern knowledge in a more Islamic fashion attract much attention in Muslim academic and intellectual circles (AbuSulayman 1989). Bakar and Nasr's views are similar, and they continue to resonate among Muslim thinkers concerned about science and Islam. In scientifically advanced countries, there is very little opposition to evolution in the academic and mainstream intellectual environments, and even the more sophisticated varieties of anti-Darwinian views tend to be muted. In contrast, the Muslim intellectual environment is much more hospitable to ideas hostile to Darwinian evolution. The view that the functional complexity exhibited by life must be due to intelligent design remains deeply embedded in Muslim intellectual culture (Edis 2004).

Therefore, it is not surprising that intelligent design, the latest version of anti-evolutionary thought developed in the United States, has attracted attention from Muslims inclined to be suspicious of evolution. In Turkey, where the public controversy over evolution has been most intense, the major books defending intelligent design have been translated and have been favorably reviewed in the Islamic press (Akyol 2005). The intelligent design literature sets scripture aside and concentrates on claiming that mindless processes such as variation and selection cannot create the information-rich structures seen in biology (Meyer 2009). This approach validates intuitions about divine design in the world common to all Abrahamic religions, including Islam.

Though Muslims have a wide variety of views on creation and evolution, the views of even politically liberal and modernist Muslims tend to gravitate toward explicit divine design. Opinion polls in Muslim countries show strong public sentiment against evolution (Hameed 2008; Miller et al. 2006). And even the non-negligible minority acceptance of evolution in such polls does not necessarily signify agreement with a naturalistic conception of evolution. Muslims who agree with common descent very often hold non-Darwinian views of evolution; it is, at present, impossible to use survey data to differentiate between acceptance of explicitly guided or progressive views of evolution and evolution as understood in mainstream science.

52.9 Evolution Education in the Middle East

Evolution becomes controversial especially in the context of education. Therefore, educational policy concerning evolution is a good indicator of official standpoints and their conflicts and alignments with popular social and political views concerning evolution. Given the wide variety of political contexts in which Middle Eastern science education policies take shape, a diverse array of outcomes can be expected. Examining evolution education provides an opportunity to see how some more general themes about Muslim responses to modern science, such as unease with apparently materialist aspects of science, play out in varying local circumstances.

Together with Turkey, the secondary biology curricula of Lebanon, Egypt, Iran, Saudi Arabia, and Israel have been relatively well investigated. Curricular studies, when combined with surveys indicating views on creation and evolution, give good snapshots of responses to controversial aspects of science at the level of students and educators. More detailed research on local histories is needed to reveal linkages to the broader ongoing debates among Muslims concerning science and religion.

Evolution education in Turkey is marked by changes imposed by different governments since the military coup of 1980, tending toward a more culturally conservative point of stability with the moderate Islamist government in power since 2002. The prominent presence of creationism for decades has clearly affected students and has led to a low level of acceptance of evolution among surveyed undergraduates (Peker et al. 2010). Research also suggests that state education policies have an important effect on the acceptance of evolution in Turkey. For example, a survey has shown that recently trained younger teachers reject evolution significantly more frequently than their older colleagues (Somel et al. 2007). The teachers' views then naturally affect their students. Turkey is a case study exhibiting a very successful anti-evolutionary movement that has found state support as well as a popular base, affecting both public opinion and educational policies (Yalçınoğlu 2009).

The teaching of evolution is treated differently in Egypt and Lebanon: while the theory of evolution is included as one complete unit in the Egyptian secondary level biology curriculum, it was eliminated from the official Lebanese curriculum because of pressures from religious authorities. However, many Lebanese students are still exposed to at least some ideas and concepts associated with the theory of evolution. Many schools in Lebanon implement international curricula such as the International Baccalaureate, the French Baccalaureate, and a variety of American curricula; many Lebanese schools adopt American or French textbooks. The secondary level Egyptian biology textbook required in all public and local private schools includes a unit entitled "Change in living organisms (evolution)" that is taught in Grade 10. As presented in the required textbook published by the Egyptian Ministry of Education (Duwaider et al. 2005–2006), the learning outcomes of the unit expect students to be able to define evolution and "improvement," differentiate evolution from "improvement," explain and critique Lamarck's theory, explain and critique Darwin's theory, explain the modern evolutionary synthesis, define the concept of hereditary balance, explain variability, define and give examples of natural selection, list different types of evidence in support of the theory of evolution, and understand that science is tentative. A close reading of the unit shows that the authors seem neutral – they present content matter and evidence in support of evolution without taking sides. The authors suggest, in the introduction to the unit on evolution, that there have always been different explanations of variability in living things and the appearance of life. They go on to explain the differences between special creation and evolution and state that the theory of evolution is accepted by most biologists, who use evolution to explain a wide range of biological phenomena.

Other Middle Eastern countries show considerable variation. Burton (2010, 2011) investigated the extent to which evolution is emphasized in the science curricula of Iran, Saudi Arabia, and Israel. Burton (2011) found that in Iran "science is not described as simply an outgrowth of Islam or subject to preconceived doctrines of any religion – rather it is affirmed as a separate valid field of knowledge, and one crucial to individual and social welfare" (p. 27). Consequently, according to Burton, the coverage of evolution does not seem to be a controversial topic, resulting in a thorough coverage of the topic at different grade levels. For example, in grade five, students are introduced to the history of the earth and life. This history is based on the work of geologists and other scientists with an emphasis on evidence in support of evolution. The same thing happens at the grade 8 and grade 12 levels where students are exposed to a thorough treatment of evolution and an assertion that almost all modern biologists have accepted Darwin's theory. The only topic that does not receive complete coverage in the Iranian textbooks is the most religiously controversial topic, human evolution.

In contrast to Iran, the science curriculum of Saudi Arabia asserts that science education is grounded in an Islamic view of the universe, humanity, and life and in a strong belief in the harmony between Islam and science (Burton 2011). As a result of the centrality of Islam in education, the Saudi science curriculum and textbooks provide ample evidence from the Quran in support of creation and emphasize the necessity of rejecting the theory of evolution because of its blasphemous and fraudulent nature (Burton 2010).

According to Burton (2010), the situation regarding the teaching of evolution in Israel seems to be in-between Iran and Saudi Arabia. While the publicly supported Israeli religious and secular schools share the same biology curriculum, religious schools are allowed to use educational materials produced by religious authorities that include references to creation, the Creator, and the special status of humans who are created in the image of God. The emphasis on creation in publicly supported religious schools appears to persist even after they study biology at the secondary school level.

Several studies have been conducted in Lebanon and Egypt to investigate students', teachers', and university faculty members' positions regarding evolution. In Lebanon, the positions of Muslims (Sunni, Shiite, and Druze) and Christians were investigated, while in Egypt Muslims (only Sunnis) and Christians were involved in the studies.

Dagher and BouJaoude (1997, 2005) explored how a number of biology majors attending a university in Beirut, Lebanon, accommodated the concept of evolution with their existing religious beliefs. Sixty-two university students enrolled in a required senior biology seminar responded to open-ended questions that addressed (a) their understanding of evolutionary theory, (b) their perception of conflict between this evolutionary science and religion, and (c) whether the concept of

Table 52.1 Students' personal positions toward the theory of evolution represented in relation to their religious affiliation

Position	Christian		Muslim		Total/position	
For evolution	82 %	(n = 14)	35 %	(n = 16)	48 %	(n = 30)
Against evolution	0 %	(n = 0)	47 %	(n = 21)	34 %	(n = 21)
Compromise	6 %	(n = 1)	18 %	(n = 8)	15 %	(n = 9)
Neutral	12 %	(n = 2)	0 %	(n = 0)	3 %	(n = 2)
Total/religion	100 %	(n = 17)	100 %	(n = 45)	100 %	(n = 62)

evolution clashed with their beliefs. Based on their responses, 15 students were selected for an in-depth exploration of their written responses. Students' answers clustered under one of four main positions: for evolution, against evolution, compromise, and neutral. As indicated in Table 52.1 above, more Christian than Muslim students were supportive of evolutionary ideas.

BouJaoude and Kamel (2009) found that Muslim and Christian secondary school students in Egypt and Lebanon had inadequate understandings of the nature of theories and of the scientific bases of evolution. Moreover, they found that there were significant differences between Lebanese Christian and Muslim students regarding their perceptions of the relationship between science and religion, with Muslims being in general more influenced by their religious beliefs than Christians. Also, while more Muslim than Christian Lebanese students rejected evolutionary science, these differences were not as pronounced in Egypt where Muslim and Christian students differed on only a few items on a survey that evaluated their conceptions of evolution.

BouJaoude and colleagues (2011b) investigated distinctions among the diversity of religious traditions represented by Lebanese and Egyptian Muslim high school students regarding their understanding and acceptance of biological evolution and how they relate the science to their religious beliefs. The researchers explored secondary students' conceptions of evolution among members of three Muslim sects – Sunni, Shiite, and Druze – in two cultural contexts, one in which the overwhelming majority of the population is Muslim (Egypt) and another in which there is a sizable Christian community (Lebanon). Data were collected via surveys that examined students' scientific and religious understandings of evolution among 162 Egyptian students (all Sunni Muslims; 63 % females and 37 % males) and 629 Lebanese students (38.5 % Sunni, 38 % Shiite, and 23.5 % Druze; 49 % females and 51 % males). Additional data were collected via semi-structured interviews with 30 Lebanese students to allow triangulation of data for accuracy and authenticity. Results indicate that many Egyptian and Lebanese Muslim students have misconceptions about evolution and the nature of science, which often lead to rejection of evolution. Also, Lebanese Sunni and Shiite students and Egyptian Sunni students tend to exhibit high levels of religiosity, and these students report that their religious beliefs influence their positions regarding evolution. Finally, Sunni and Shiite Lebanese students have religious beliefs, conceptions of evolution, and positions regarding evolution similar to those of Sunni Egyptian students.

BouJaoude and colleagues (2011a) investigated biology professors' and teachers' positions regarding biological evolution and evolution education in Lebanon.

Table 52.2 University professors' positions regarding evolution categorized by religious affiliation

	Muslim					
	Shiite	Sunni	Druze	Christian	Agnostic	Total
Accept	1			2	1	4
Selectively accept		2	1			3

Table 52.3 Teachers' positions regarding evolution categorized by religious affiliation

	Muslim				
	Shiite	Sunni	Druze	Christian	Total
Accept			5	4	9
Reject	3	1		1	5
Selectively accept	2	1			3
Neutral (noncommitted or confused)		2		1	3

Participants were 20 (13 private and 7 public) secondary school biology teachers (16 females) and seven university biology professors (two females and five males) teaching at a private, American-style university. Data came from 25 to 30 min, semi-structured interviews with the teachers and the professors. As shown in the tables above, university faculty members (Table 52.2) were divided between those who accept (4 out of 7) or who selectively accept (3 out of 7) the theory of evolution with more Muslims being selective in their acceptance. As for teachers (Table 52.3), the positions ranged from acceptance to total rejection with more Muslim teachers rejecting the theory than Christian teachers.

There is considerable variation in science education policies among Muslim countries and populations in the Middle East, reflecting a wide variety of local histories and religious influences on the politics of education. Nonetheless, there are some important commonalities. Those aspects of modern science that have a materialist association, especially biological evolution, meet with opposition at many levels. Therefore, even when evolution is taught in conservative Muslim environments, this usually takes place in a context where a creationist alternative is a prominent implicit presence. Iran is a partial exception, perhaps due to local Shia dominance allowing a degree of intellectual independence from Sunni resistance to evolution and the explicit Iranian state support for developing advanced biotechnological capabilities.

52.10 Separating Science and Religion?

The recent Turkish and Arab experiences with friction between science and religion partly derive from a common history as successor states to the Ottoman Empire, having undergone broadly similar historical experiences with Western colonial powers and facing a similar need to import science and technology from non-Muslim sources. In formulating religious intellectual responses to a perceived materialism in parts of modern science, and in developing highly successful varieties of opposition to evolution, Turkey has perhaps been at the cutting edge, due to proximity to Europe and the history of the Turkish experiment with secularism. But much of what can be said about Turkey applies to the Arab Middle East and beyond. For example, while Islamic creationism has acquired a Turkish flavor of late, this has not reduced its international appeal. Conservative Muslims worldwide, in South Asia as well as the Middle East, denounce materialism, sometimes using the stimulus of Harun Yahya to activate local objections to how modern science has removed divine purpose from its conceptual frameworks (Riexinger 2009).

Indeed, Harun Yahya creationism as an international phenomenon illustrates how, in the age of the Internet, doctrinally conservative Muslims concerned about materialist aspects of modern science rapidly interchange ideas and formulate responses that have global resonance. In some respects, the Harun Yahya corpus shows the marks of its Middle Eastern and specifically Turkish origin, as in its many books and pamphlets devoted to praise of Said Nursi and themes popularized by the Nur movement. And yet, especially the creationist Harun Yahya material, though it originates in Turkish, is immediately translated into English and languages of the Muslim diaspora as well as Muslim-majority countries. It is made available globally through well-designed websites and advertised and popularized throughout the Muslim world.

More serious Muslim thinkers about science and religion also have an international audience. Seyyed Hossein Nasr is not an obscure academic from Iran who now teaches in the United States – his views on achieving an Islamic philosophy of science are known and debated by interested Muslim intellectuals worldwide. Notions such as "Islamizing science" or using the anti-Enlightenment aspects of postmodern philosophy to defend Islamic traditions against science-based critiques (Aydın 2008) are, again, put to use and discussed globally. There are, naturally, local differences of emphasis, and local education policies are affected in various manners depending on diverse political circumstances. But the *intellectual* options available to Muslim thinkers today are everywhere alike. With the rise of a globalized Islam constructing a universal religious identity transcending local variations (Roy 2004), the discussions young Muslims enter into online concerning science and religion also sound similar themes. Indeed, populations that operate in a globalized economy, and most keenly feel the effects of technology on their lives, are the strongest constituency for today's efforts to harmonize modern science and traditional religion. They have the most at stake.

So a broad-brush description of conservative Muslim views of science and religion today should be appropriate. Muslim populations typically are positive toward technology. Though religiously informed criticisms of the uses of technology are not unknown (Sardar 1984), doctrinally conservative Muslim intellectuals – who usually take modern social conditions for granted – almost always support science rhetorically. But many also harbor distrust toward the present conceptual frameworks of science, which appear as "only theories" compared to the compelling facticity of the products of applied science. Therefore, conservative Muslims often find it easy to reject aspects of modern science that appear tainted with materialism or that otherwise challenge traditional beliefs.

Broad-brush descriptions must always overlook local variety and important details. But more important, even if it is true that modern science and popular forms of Islam have significant points of friction, the consequences for science and education are not immediately clear. After all, the United States also exhibits a strong degree of religious conservatism in its population, including a high and steady level of support for creationism. Scientists have plenty of occasions to complain about how Americans are scientifically illiterate, how they see science as a way to collect "facts" like stamps, and how they are enthusiastic about technology but often take an anti-intellectual attitude toward the conceptual frameworks of science. Some scientists even directly blame American religiosity for all this (Coyne 2012). And yet the United States supports world-class scientific and educational enterprises.

But the United States is also different from Muslim lands. In the United States, populist opposition to knowledge-based elites, such as that expressed by Christian creationism, is isolated from the intellectual high culture and has little effect on scientific institutions. The strength of liberal religious options also helps to protect science from religious populism, supporting a conventional wisdom according to which science and religion have separate spheres that do not interfere with one another.

In that case, perhaps a Muslim version of a separate spheres or "nonoverlapping magisteria" doctrine (Gould 1997) could help satisfy both desires for religious authenticity and scientific interests in describing how the natural world works. After all, there is no shortage of Muslim scientists who insist that their scientific commitments, including evolutionary biology, are perfectly compatible with their faith (Guessoum 2011). When Turkish academics publicly defend evolution, they usually express views similar to positions taken by American organizations such as the National Center for Science Education, endorsing liberal theological stances and advocating separate spheres (Aydın 2007). A few internationally known religious intellectuals, such as Abdolkarim Soroush, argue on a religious basis that science should be independent of religion (Soroush 2000).

The separation option is still possible. As the world of Islam continues to change rapidly, a strict separate spheres view may become more prominent in the future. But at present, this option is structurally weak and discredited by its associations with political secularism. In Turkey, defenders of evolution are disorganized and demoralized. And throughout the Muslim world, liberal theologians invite conservative reactions. Soroush, for example, was pressured to leave Iran; he now teaches in the United States.

Moreover, emphasizing the prospects for a separation of science and religion in Islam may lead to a distorted picture of specifically Muslim responses to science. The notion of separate spheres has been a successful device to keep the peace between science and religion in the post-Christian West. It may not be as applicable to a Muslim world where religiously conservative intellectuals are determined that they should not come to live in a post-Muslim environment. An insistence on separate spheres would be an imposition of a Western perspective onto Muslim concerns, when Muslims are trying to achieve a non-Western way of being modern. There is a strong tendency to see the present intellectual distance between science and religion as being a Western solution to a Western problem caused by factors inherent to Christianity (Aydın 2000; Şahin 2001). Very often Muslims gravitate toward the notion that since science and religion must coexist in harmony in an

Islamic context, perhaps as in the supposed golden age of medieval Muslim science (e.g., Al-Hassani 2012), there is no problem here to solve.

So conservative Muslim resistance to materialist conceptual frameworks in science deserves to be taken seriously. It is easy to observe that popular Muslim apologetics typically has very low intellectual quality. Recurrent worries about materialism can also seem odd. After all, Marxism has nearly vanished. There are some readers of Richard Dawkins translations, and among secular philosophers and scientists in Muslim lands, there are no doubt even outright physicalists. But all such materialists have negligible wider social influence. Nonetheless, there is also some real intellectual substance articulated in Muslim concerns about materialism.

The conventional wisdom among Western liberals both accepts and conceals conflicts between robust Abrahamic theisms and the naturalism that has come to characterize modern science. If divine purpose has no explanatory role in physics or biology or neuroscience, it becomes hard to see how to make sense of a claim of divine creation. Western liberals accept this difficulty but usually propose to overcome it by having supernatural belief retreat to a metaphysical realm. Religion handles ultimate meaning and purpose, while science investigates the details of how nature operates. This is an intellectually unstable position, since both religious and scientific thinkers usually have ambitions that cross over into each other's territory (Edis 2006). Moreover, Western liberals have inadvertently ended up giving science primacy over religion, in the sense that when a conflict has appeared, as over creation and evolution, it is always theology that has had to retreat and reinterpret. Many Muslims who are aware of the liberal Christian response to science cannot help but perceive it as a bowdlerization of revealed truths.

Conservative Muslim intellectuals affirm science as a form of worldly learning, but they often insist that science should be anchored in Islam. Inquiry should be free but only as long as it respects the boundaries set by faith. Muhammad Abduh, the Egyptian modernist, praised Islam as a religion of reason, saying Islam "did not impose any conditions on reason other than that of maintaining the faith" (Euben 1999, p. 106). This is a common sentiment, surfacing in legal reasoning as well as intellectual debates (Kamali 1997). To Western liberal eyes, it looks like free inquiry has a very important exception, since core Muslim beliefs are not open to question. But many Muslims would reject that framing of their views. By protecting Islamic beliefs from criticism, they see themselves not as carving out an intellectual exception but as protecting reason itself. Both in intellectual culture and at a popular level, Muslims very often think that some awareness of divine laws is constitutive of rationality itself (Rosen 2002). Critically examining religious beliefs invites doubt. And casting doubt on God or revelation can lead to nothing but irrationality and social disintegration.

So even with the religious experimentation taking place among Muslims today, it remains very uncertain whether Muslim views of science and religion will follow a trajectory toward a separate spheres style of accommodation. It is, for example, possible that Muslim populations will continue to gravitate toward a different equilibrium between supernatural beliefs and modern knowledge, one that emphasizes applied science while downplaying the conceptual frameworks of natural science. Whether this is sustainable will depend very much on future opportunities for technological creativity independent of developments in basic science.

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Chapter 53
Indian Experiences with Science: Considerations for History, Philosophy, and Science Education

Sundar Sarukkai

The topic of science and science education in the Indian context encompasses many themes. This chapter will mainly focus on how the disciplines of the history and philosophy of science (HPS) can contribute to the debates in science education (SE) with specific reference to the Indian context. The extensive literature on the role of HPS in science education is comparatively recent. As Turner and Sullenger (1999, p. 10) point out, it is only in the nineties that there was a sudden proliferation of publications in this field. However, very few, if any, deal with the specific relationship between HPS and SE in the Indian context.

Why should this extension to the Indian context be of any interest to the community of science educators? Here are two answers: the first is that in the case of SE in India, it is primarily HPS which can help question the enduring claims that science is a Western enterprise and one that is unique to the West. By doing so, we bring in other cultural practices within the boundaries of science thereby extending the ownership of the essential characteristics of science to other non-Western cultures. Secondly, the Indian experience with science exhibits many stark differences from the European experience, and thus the lessons from a HPS that is responsive to these experiences will potentially offer new contributions to global SE. This chapter will illustrate how both these modes of intervention are possible. Invoking HPS is a powerful way to "localize" science and give a sense of ownership to scientists and science teachers. But in doing this, the HPS community itself is challenged for HPS traditionally has ignored the historical and philosophical contributions from the non-West.

The fundamental questions which frame the discussion here are the following: Does history and philosophy of science matter to science education? Do insights from Indian experiences with science matter to this debate?

There is a larger context in which these questions should be placed and that is the aims of science education. Does science education have the same aims as

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education? This cannot be – or at least is not seen to be – given that the larger aims of education include moral education and cultivation of human sensibilities. Science education seems to have become completely about the subject matter of science alone. It has been reduced to the teaching of the content of the various disciplines of science. Even history and philosophy of science are banished from science teaching. In this context, the real question that should be asked is this: Should science education be a handmaiden to the aims of science or should it have an autonomous agenda of its own, one that is more in tune with the aims of education in general?

This chapter makes the following argument. Even if restricted to the subject matter of science, it is possible to make the following observations. The decision of what subject matter to teach, the way to teach it, the background information on that content, and the many decisions of inclusion and exclusion of the content, and evaluation – all of these are based on certain presuppositions. There are hidden assumptions about the nature of science as well as the "invisible hand" of specific histories and philosophies of science in every science lesson.

To claim that HPS is not relevant in the content of science teaching is to ignore these hidden presuppositions. Thus, a call to include HPS in SE is only a call to make these hidden assumptions visible. Once this is done, the immediate relevance of the Indian (and other cultural) experiences to science teaching becomes obvious.

53.1 The Role of History and Philosophy of Science in Science Education

There have been many writers who have suggested the use of history and philosophy of science in science education.[1] This topic is central to science education for it confronts the basic questions of education: What does one teach in science and how does one teach science? It has also led to the question of whether nature of science (NOS) is relevant for the teaching of science, a theme which will be pursued later in this chapter. However, the impact of HPS on science education has been quite limited. In the Indian case, it is even more so. The reasons underlying this indifference illustrate the unique challenges of science and science education in India. Some of these reasons have to do with the very understanding of what constitutes science, the task of education in general and that of science education in particular, the complex histories of the idea of science, and its relationship to tradition and State. This and the following sections will address some of these issues with the fundamental objective being the following: Can the Indian experience with science from ancient times to the present add new insights and new themes to the debate on the role of HPS in science education?

Matthews (1989) argues for the importance of HPS in science teaching (ST). However, he also notes an enduring problem in establishing the relevance of HPS

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[1] See Duschl (1985, 1994), Hodson (1988, 1991), and Matthews (1989, 2004).

for ST, namely, the "failure of science teaching to disturb ingrained beliefs" (ibid., p. 5). As he points out, it seems to be the case that students study science for their exams but use different belief systems for "everyday life." This is a "problem" that is very much a part of Indian school system. Moreover, the tendency to bifurcate the domain in which one practices science and the other in which practices contradictory to science are prevalent is not limited to students alone. In India, this is an integral part of scientific institutions also.

As far as the impact of philosophy of science on SE is concerned, it is arguably Kuhn who has had the greatest influence. Matthews (2004) discusses how Kuhn was ignored early on after the publication of his book, *Structure of Scientific Revolutions*, but in the post-seventies, the science educationists caught on to Kuhnian ideas. However, given the skewed understanding of the nature and practice of science, these ideas were most successfully used in the program of constructivism. The SE community seems to exhibit this constant tension of drawing on HPS but at the same time not being sufficiently trained to draw on it properly (ibid., p. 112). So it seems as if the community of science teachers either ignores HPS or jumps on to certain trends such as constructivism and relativism. One might think that perhaps history of science is better accepted as compared to philosophy of science. But, as Rodríguez and Niaz (2004) point out, science textbooks continue to ignore lessons from history of science. By analyzing the description of atomic structure in general physics textbooks published in the USA, they show how science textbooks continue to ignore the rich narratives of experiments available in the history of science on this topic.

Two of the more successful themes drawn from HPS relate to the NOS debate and a richer description of rationality, and their relationship to both science and education.[2] Although certain notions of rationality have come under attack, nevertheless there has been a sustained belief in the rationality of science as well as its importance in the idea of education. Siegel (1989) points out that critical thinking is the essence of education and through the idea of rationality he brings HPS and science education closer to each other. He considers critical thinking as the "educational correlate" of rationality (ibid., p. 21) and as an "educational ideal" (p. 27). Furthermore, he identifies "reason" as the common element of rationality: "a critical thinker is one who appreciates and accepts the importance and convicting force of reasons" (ibid., p. 21). The invocation of reason and rationality as important themes in the relationship between HPS and SE will be useful when we consider Indian philosophical traditions later on in the chapter.

The second theme – the debates on NOS – has been largely catalyzed by work in HPS, but there remains an open question as to whether NOS is relevant at all to science education. Turner and Sullenger (1999) point out how the divergent descriptions of NOS within science studies has had a negative impact in that it has led teachers to draw on this theme in a fragmented manner. There are many reasons why HPS does not make an appreciable dent among science teachers: for example, teachers resist them because they take away time from core teaching of science subjects (p. 13), science teachers themselves have little knowledge of or training in

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[2] See Carey et al. (1989), Jenkins (1996), and Machamer (1988).

HPS, and because "teachers share many scientists' disdain for what they regard as soft add-ons" (p. 13). Science and technology studies (STS) are also not accepted by the community of science teachers because of the belief that discussions on science (through NOS) often end up as discussions on "law, economics, religion and power politics" (p. 16). This has led to teachers in many countries rejecting the role of HPS in ST. As these authors note, "Educational theory requires consideration of at least three factors: curricular content, instructional methods and approaches, and learning theory" (p. 17). They believe that HPS and STS have "emphasized" the first two but have ignored the third. In India too, there is continued indifference to HPS among science educationists. Although the National Curriculum Framework (2005) engages with the theme of nature of science and science education, there is little progress on the ground.

What is most surprising is that in the extensive global literature in this area, there is little that draws on other scientific traditions in order to pose the question about the nature of science. Did the Arabs, Indians, and Chinese do science the same way as the Europeans did? Did the Europeans have a unified idea of science at any time? Do the practices and notions of science in Asian and Arabic civilizations matter to the debate on NOS and science education? Does the HPS formulation of NOS continue to propagate the belief that "modern" science arose only in Europe since it draws only on a "Western" history and philosophy of science?

These questions become more urgent given some worthwhile historical challenges to the traditional view of science. The argument for the multicultural origins of science, a view that is still at the periphery of the mainstream history of science, necessitates changes that should be introduced in the nature of science debate. As far as philosophy of science is concerned, philosophical insights drawn from a consideration of Indian science and technology can illustrate how differing views of science and scientific methodology are articulated in other cultures.

Will science education get enriched by drawing on these diverse HPS traditions? Given the unique characteristics of the Indian society as well as its experiences with the notion of science, it should not surprise us to discover that a dialogue between HPS (one that is sensitive to these experiences) and SE leads to a new set of issues, some of which will be discussed below. If there is one particular issue that is at the heart of this dialogue, it is one on the definition of science. In a fundamental sense, unless we come to an agreement as to what constitutes science, it is not really possible to broaden the discussion on SE. It is precisely this question of demarcating science that is at the core of debates in non-Western cultures. Did these cultures "possess" science and technology before "modern science?" If so, how should these traditions be factored in SE? The sections that follow offer challenges to traditional views on science that locate it as part of a European tradition, following which their relevance for the NOS debates in SE is discussed. These arguments are placed within the larger context of defining science and the challenges of taking ownership of science, both of which have implications for science curriculum and pedagogy. Finally, the last two sections give an indication of some specific ways of "using" insights from Indian philosophical practices for SE.

53.2 The "Invisible Hand" of the Histories and Philosophies of Science in Science Texts

The most important rationale for taking HPS seriously in SE is that there is already a hidden domain of HPS in SE. There are many levels of the unarticulated presence of HPS in science texts. First of all, the content in a science text is already a product of a judgment of what constitutes science. For example, a textbook in physics presents certain subject matter as if it belongs unquestionably to the discipline of physics. On what basis is this judgment made? What content in physics, chemistry, and biology, for example, is chosen and on what basis? Why are certain subjects chosen as illustrations of science? A quick answer to these questions is that the scientific community decides what is science, what comes under physics, and so on. But this is to make science education secondary to the aims and ideology of the scientific community. If this is the case, then teachers function as mere conduits in a larger project of international science.

Consider a text in physics which contains Newton's laws of motion. Typically, there will be no historical or philosophical considerations which lead to the statement of these laws. Science texts, even today, present these laws as if they are ahistorical and appeared to Newton suddenly. There is no mention of a long history of motion, including interesting theories from Indian philosophies. Concepts that are used in the text including seminal ones such as mass, force, and energy, usually appear without any historical description. The fact that these concepts appear in other non-Western cultures is forgotten. In a science text, the choice of the content, the way the content is presented and ordered, and the choice of concepts and that of their definitions are all based on particular views of science, which themselves reflect particular histories and philosophies of science. For example, one such implicit assumption is that non-Western science is not really science.

Consider the following presuppositions that are at the core of science textbooks. Firstly, there is a standard history of science that is implicitly accepted. This history begins normally with Copernicus and goes on to Galileo and then Newton, with some mention of Aristotle and some "Greeks" thrown in. This history influences – greatly – the choice of the content of the text. And even within this story, there are many acts of omissions based on what story of science is chosen to be presented in the text. Similarly, the break between science and religion is an important part of this narrative. This is linked to the standard narrative that relates science to Western Enlightenment. The idea of the conflict with religion is often a selective rendering of a much more complex history of modern science's relationship with religion, as are the specific history of concepts that are presented in these texts.

There are larger themes which are also presupposed in these choices. For example, the philosophical assumptions of Platonism are an integral part of mathematics teaching. This worldview intrudes into the construction of the text in as many ways, including the structure of the problems, modes of evaluation, and the way mathematics is introduced. Mathematics is developed in a completely different manner in Indian and Chinese mathematics, but this material will not be found in textbooks. For example, the ways by which irrational numbers and negative numbers are conceived in Indian and Chinese mathematics illustrates alternate approaches to Platonism.[3]

Another invisible theme is the belief that European rationality characterizes science. There are many ways by which this idea is encoded into textbooks. One obvious manifestation of it lies in the almost complete absence of the mention of any non-western historical figure in the list of scientists and mathematicians mentioned in these texts. Along with this absence, there is an explicit emphasis on the figures of Western Enlightenment.

Yet another major theme is the belief that scientific content is universal and that science texts need not take into account the locale specificity of the students or the teacher. This also allows the propagation of these Eurocentric myths without second thought; this has led to generations of students in non-Western societies to believe that their cultures have had no contribution to the science of the modern world.

One may rationalize these choices by pointing to constraints of space in a textbook, access to material, and so on. However, it is the case that these constraints also influence what is taught *as* science. These constraints are also product in a textbook of specific choices which often reflect hidden presuppositions about science. All these choices reflect specific beliefs based on particular histories and philosophies of science and thus can be challenged on many counts as listed below.

First is the choice related to the material that is seen to constitute science. Should one choose to mention the rich domain of Indian metallurgy and technology in ancient times as well as later Chinese technologies? The extensive material on Indian mathematics, including Kerala mathematics, the complex and rich classification of botanical information in various indigenous traditions, and the vibrant practices of chemistry which rival similar practices in Europe of that time are all examples of science that are potential subject matter for science texts.[4] Anybody who is exposed to the multicultural histories of science will be able to appreciate the claim that the origins of science in Europe are indebted to the transmission of knowledge from different traditions including the Chinese, Arabic, Indian, and the Greek. To not integrate these histories into the content of science is to take a particular philosophical position about science and its subject matter.

Next, consider the history of fundamental concepts that are taught in texts. There is almost no recognition or acknowledgement that some of these concepts like mass, inertia, motion, energy, force, and causality have different formulations in non-Western cultures. Textbooks still talk of ideas like mass and force as if they are apples that dropped on Newton and other scientists from the tree of knowledge.

Moreover, the prevailing background of all discourse on science is based on some naive ideas of European rationality. Even today, scientists (and many science educationists) continue to believe that there is something special to this rationality and that alternative rationalities are not possible. Under tremendous pressure from extreme relativism, they might now acknowledge that perhaps other cultures

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[3] See Dani (2010) and Mumford (2010).

[4] Details are given in the next sections that follow.

possessed some rationality but none of this has been factored into the basic texts in science. But, if European rationality is privileged, then the full story must also be noted. There is another use of rationality that should be taken into account in these claims: the notion of rationality was central to the European intellectual project as a way to distinguish European cultures from other cultures. Their claim to rationality was fundamental to the colonial project for through this category they could articulate their claim to being superior to other colonized cultures. In a powerful metaphor, they constructed themselves – because of this rationality – as adults and the colonized as children who needed the guidance of adults. So when the idea of rationality is repeatedly invoked, these two problematical characteristics are forgotten: one is the hegemonic work which rationality did and does, and the other is the existence of other equally important structures of rationality in other cultures. The examples of Indian logic and its mathematics are enough to indicate these possibilities; they will be discussed in greater detail in this chapter.

So the fundamental question is this: On what "rational" basis do science educationists make a choice when confronted with these new global histories and philosophies of science? If we look at how the Indian State confronted this issue, one can see how the ideology of universal, European science influenced and continues to influence science education in India.

53.3 Science and the State

History of education has as much influence on SE as does history of science. In India, students are taught science in a culture in which science is highly valorized. They tend to believe that they learn science because it is associated with virtues such as truth, knowledge, rationality, and power, virtues which are reinforced in the curricula. These virtues are those that are transmitted to the students by different agencies including the government, public space, peer groups, teachers, and parents. The strengths as well as the weaknesses inherent in SE are catalyzed by these different interest groups. Science educationists may find it useful to understand the context in which students are being taught science as well as the context of the educational methods to which they are subjected. In the Indian case, it is therefore necessary to consider the historical and ideological trajectory that sets into place educational practices in science. The most important influence on the institution of education is the colonial one, later followed by the independent nation.

The State (both pre and postindependence) was the primary patron of science and education. Sangwan (1990) analyzes some of the complexities in understanding the changing views on education in British India. He identifies three phases: in the first phase, the rulers did not change the system in India; in the second phase, they actually supported "oriental literature and science"; and in the third phase, they provided stronger support for science education. It is important to note that there was also a growing support among Indians for the Anglicization of education. As Sangwan notes, a group of influential Indians in Bengal "exhibited its revulsion" when the British supported Indian educational practices (particularly Sanskritic education) at the expense of "modern" education. But the British continued their support of "oriental education" in spite of protest from influential members of Indian society. Interestingly, the third phase, when European education was established, was also based on the belief that "modern" education would train Indians to support the activities and interests of the company rule, for example, to fulfill the demand for engineers and training of people to run the railways. Moreover, following the ideological interests of Macaulay, there was an overemphasis on teaching European literature and science, at the expense of indigenous science and knowledge systems. This was not conducive to science education since, as Sangwan notes, "what made things worse was their attempt to propagate English education rather than science education in India" (ibid., p. 89).[5]

There were also important changes introduced in the colonial era in the field of education. These changes, according to Kumar (2009), continue to influence educational practices even today. One such was the emphasis on textbooks and the introduction of a particular kind of textbook culture in Indian education. Kumar points out how textbook dominates curriculum and traces this attitude to the British colonial administration who saw education as a way to train Indians in "European attitudes" as well as "imparting to them the skills required for working in colonial administration." The insistence on textbook replaced traditional forms of education in which the teacher had freedom to choose what to teach. Kumar points out that in this colonial system, teachers also had to function as administrators. There were also punitive measures on teachers. Similar attitudes towards examinations and evaluative practices which were introduced by the British continue even today. For many educationists, these practices have been the bane of education in India today, particularly in science education.[6]

Postindependence, there was a calculated emphasis on science education. In so doing, the State was following colonial and modernist beliefs that science and rationality were external to Indian culture and that Indian society was characterized by irrationality and superstition.[7] Science education was to be the cure for this cultural "disease." The belief that science would be the vehicle for development meant that education in India would be skewed towards science education. Nothing defines the Indian State's engagement with science as well as the Constitution of India. At the dawn of the Indian independence, the Constitution was framed with the help of some of the most important intellectuals and freedom fighters at that time. Like most other Constitutions, the Indian Constitution is perhaps the most important public document in modern India. But unlike other Constitutions, this one has an intriguing clause listed in the constitutional duties of all citizens. One of

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[5] See also Kumar (1980).

[6] See Kumar (1988). See also Dharampal (1983) for a brief discussion on education practices in eighteenth-century India.

[7] See Arnold (2000) for a discussion on the relation between modernity and science in India. Prakash (1996) discusses the support of the Indian elite to science as an exemplar of modernity. See also Habib (2004) for Islamic science in nineteenth-century India.

the constitutional duties of citizens is to cultivate scientific temper. Article 51A(h) of the Constitution of India states the following under Fundamental Duty: "To develop the scientific temper, humanism and the spirit of inquiry and reform."

To understand science education in India it is important to recognize the factors which made the authors of the Constitution to introduce this clause in the Constitution. First of all, this constitutional duty to "develop the scientific temper" reflects a fundamental aim of a new India, which was to reform its traditional societies and practices. Science becomes a way to reform a society which was seemingly suffused with superstition and irrational practices. Science, along with a particular view of the Western civilization, would liberate Indians from their past. Nehru's observation, as the first Prime Minister of free India, that industries would be the temples of the new India has often been quoted to point to a fundamental shift towards science and technology as the harbinger of a new society, one in which science would be used to better the economic state of the country. The government's support for the sciences immediately postindependence led to a large number of scientific institutes under the support of the government, including the atomic energy program under Homi Bhabha.

Since education was also primarily under the government, this view of science, as an agent of social change and development, as well as a reflection of a superior intellectual virtue special to the West, began to get propagated in schools and colleges. Even in the public sphere, science continues to be projected in these terms thereby adding to the social value of doing science. Since science was viewed as the agent to get rid of traditional beliefs, this led to the piquant situation of using science to erase any vestiges of ancient and medieval Indian intellectual traditions in the educational system, particularly in SE. This erasure is reflected in education at all levels in India leading to a chasm between postindependent India and precolonial India which remains to this day unbridged.

Alongside these ideological connotations of science, some influential Indian politicians too believed that national development meant promotion of science. The early models of development were all technology driven: thus the big dam projects, atomic energy program, the agricultural "revolution" through the use of technology, and so on. All these ideas of development clashed with traditional practices, particularly in the fields of agriculture and medicine. However, the State's commitment to a particular mode of development, one in tune with the rest of the developed world, meant a concomitant support to science and science education.

In spite of the early fervor of the leaders of the new nation, the public reception of science has been quite ambiguous. The claims that science education will eradicate social inequalities, remove caste system, and in general make people "rational" have remained just that. In fact, the greatest challenge to scientific temper in India comes from many of the scientists themselves, who while being good scientists are also committed religious believers. Such a dichotomy is well exemplified by the problematic example of offering prayers to machines.[8] Embodying the spirit of

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[8] See Sarukkai (2008).

contradiction which seems to characterize an Indian way of thinking, scientists too easily wear contradictory roles of being a scientist as well as a religious person.[9] Many of them consult astrologers and visit religious institutions for family functions without that reducing their competence and standing as a scientist in their disciplines.

In the Indian scenario, the public space in which science gets articulated is a complex one. Interestingly, this public space also has religious elements within it. The relationship between religion and science in India is a complex one and historically challenges some standard history of science accounts of this relationship.[10] In the long history of science in India, it would be very difficult to actually find any cogently argued opposition to religion in doing and practicing science. Postindependent India, this opposition has been articulated by the Left as well as people science movements, but very often, this has been done with a certain amount of modernist understanding of science where science is an exemplar of rationality and religion that of superstition. Concomitant to this is the belief that ordinary citizens of the country were immersed in such superstition and it was the task of science (supported by the State) to "liberate" these citizens. Unfortunately, the scientists themselves were not up to the task demanded by these groups.

The popularity of science and technology education in India has largely been based on the easier availability of jobs from such education. However, the fact that science institutions, and science education in general, in India are excessively dependent on English means that there is a lack of democratic access to science education. This problem is compounded given the lack of good translations of science texts into other languages. These and other related factors contribute to the belief that science is not something "Indian"; they might also explain why the larger culture continues to ignore artificial expectations such as scientific temper, why the society does not buy into the story that science and religion have to be contradictory, and why there is an embarrassing lack of innovation in science and technology in India today.

Paradoxically, this is also a time when the government has increased its support to science education in an unprecedented manner, particularly in higher education. But almost all scientists and educationists point to certain well-established pedagogical practices as the bane of science education in the country. Rote learning continues to remain the dominant mode of learning in schools and many times in higher education as well. Critical thinking, including the capacity to critique, to build, and to innovate, is largely ignored in pedagogy, whether in science or other fields.

Ironically, the impact of science education on the larger public seems to be quite divorced from the cultivation of scientific temper. India, arguably more than in any other period postindependence, is in the throes of religious revivalism. There is a perceptible shift towards many traditional modes of learning, traditional practices of medicine, and also of some traditional social norms. Some feel that this is a reaction to the "imposition" of science and a corresponding rise in social problems related to

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[9] A.K. Ramanujan's essay (1989) is often quoted in this context.

[10] See Kapila (2010).

modernity and technological development. Earlier views of science as liberating society from traditional practices, which gave way to the belief that science would be the harbinger of national development, has now changed to the belief that science is a pathway to jobs in the global market. Science education reflects this confusion at the highest level: What really is the goal of science as a national enterprise? An answer to this question is not under the purview of this chapter but an awareness of this issue is important for future State interventions in science education. With this larger background of science in India, the remaining sections will deal with the relationship between HPS and SE, and through the contours of this debate develop some India-specific themes that could be of interest to the global SE community.

53.4 Science Education and the Definition of Science

One of the problems in the understanding of science in India lies in an enduring cultural belief that modern science is a Western invention. Moreover, a sustained claim from European scholars that Asian cultures did not possess the requisites for being scientific (or equivalently, did not possess the capacity for being rational or theoretical) reinforced the outsider status of science in these societies. It is indeed surprising that scholars ranging from Locke to the German philosophers, Husserl and Gadamer, repeatedly question the availability of rationality and science to Asiatic cultures. This claim also becomes an integral part of the colonial discourse; thus for a few centuries, both within India and outside, there is a well-established tradition of scholarship that not only questions the existence of science in India but also questions the capacity of Indians to practice science.[11] Thus, it was no wonder that some science texts still continue to propagate these beliefs by emphasizing science as a Western "invention" and reinforcing this by primarily citing non-Indians as examples of scientists. One of the greatest challenges for science education in India is to convert the status of science from an outsider status to an insider one. While science teachers might see this issue as being irrelevant to the teaching of the content of science, in fact it is the exact opposite. If students do not take cultural ownership over science and if they do not think that they have a stake in the production of science, then it affects how they learn science and what they do with it. Learning has to have a sense of cultural confidence associated with it. Many scientists in India tend to believe that the lack of pioneering research (as exemplified by the lack of Nobel Prizes in the sciences or Fields Medal for scientists working in India postindependence), even after decades of massive support by the State to science in India, is an illustration of the lack of confidence and not taking ownership of science.

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[11] See Gadamer (2001), Ganeri (2001) for the early European response to Indian logic; Adas (1989) and Alvares (1991) for the Western view on Indian science and technology; and Halbfass (1988) on the encounter of civilizations.

While there will be disagreements on this prognosis, it is nevertheless the case that science continues to inhabit the space between the inside and the outside in Indian society. This has serious ramifications on science teaching. For example, it is well known that scientists as role models influence young students. Science as a collective enterprise has recognized that creating legends out of scientists is a powerful way of attracting students to the field. Through the stories of these scientists, many popular notions of science, scientific method, and the idea of genius get communicated to the students and the larger public. The creation of the image of science in popular media is an important part of its success as a global enterprise. In this context, what happens to students who find few Indian models of great scientists? What is the lesson that is being communicated when all the scientists they encounter – the ones who have created new disciplines, new theories, and discovered new worlds of science – are predominantly non-Indian? This empirical fact coupled with the enduring hint that non-Western societies do not have an intrinsic capacity for being rational and scientific leads to a crisis of confidence in science learning. The often quoted comment from across all layers of society that a scientist is legitimized when she/he is first recognized in the West has become a cultural truism for other fields also.[12]

As much as research, this ambiguity about science has affected science teaching and learning, and this problem is primarily about the definition of science. Although over the past few decades there have been some seminal works on ancient and medieval Indian science (Adas 1989; Alvares 1991; Dharampal 2000), they are rarely incorporated into science textbooks. Part of the reason is the discomfort in viewing ancient or medieval discoveries and inventions as belonging to science. The problem of defining science is part of the larger theme of the nature of science. In India, this problem has two faces: one is the claim that some "disciplines" like astrology are also science, and the other is the scientificity of certain ancient and medieval practices and traditions. On both these counts, there is much denigration, particularly from the scientific community, and this is reflected in the general absence of any reference to Indian traditions of science within mainstream science.

One response has been to create a category called "indigenous science"; another is the category of "ancient science." Indigenous science has largely been reduced to innovations and modifications to "technologies" of the home and the community. It is largely artisanship and lacks some of the essential characteristics that define science – at least the definitions that constitute "mainstream" science. As innovations, they are largely experimental and technical, and do not exhibit any theoretical inclinations. This very category of "indigenous science" however illustrates an interesting way to appropriate the name of science into activities that have largely been excluded from science. This has also led to significant public movements on alternate technologies based on these indigenous and ancient technologies. However, the absorption of these movements into mainstream science education is still largely absent.

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[12] A report in 1992 points out how around 80% of scientists in research institutes in India preferred to publish abroad and "hardly published" in India. See http://dspace.rri.res.in/bitstream/2289/3643/15/Chapter%208.pdf

But what really was the status of science and technology in ancient India? Should those practices be called science? Should they be called technology? And does all this matter to the problem of defining science, definitions that are relevant to teaching science? These questions are important for our understanding of science. Most science books begin with narratives of science in which Thales, Democritus, Socrates, Plato, and Aristotle are invoked as the fathers of science. Sometimes, they are even referred to as scientists. The absence of other cultural representatives in this story of science is inimical to the teaching of science, especially in those cultures which are excluded from a stake in the ownership of science and scientific rationality.

This is ironical, especially when we consider that the theoretical foundation of the sciences was integral to the philosophical traditions of the Hindus, Buddhists, and Jains in ancient India. All these traditions were fundamentally empirical in character and focused primarily on the nature of knowledge. Description of logic was an essential part of this analysis, and even logic was not immune to empirical inputs. The rich contribution of the Hindu, Buddhist, and Jaina philosophers illustrates their attempt to give a foundation for what we would call as scientific methodology today.[13] Alongside, there was a flourishing technological world which saw the world's first invention of steel, zinc, and alloys (such as the five-alloy process).[14] Indian mathematics not only gave the foundations of mathematics to the Arabs which then found its way into Europe, but the Kerala mathematicians also described the first modified heliocentric model (like the one proposed by Tycho Brahe) and the first conceptual ideas related to calculus much before they were known in Europe.[15] Another important marker of science was in the Indian medical systems such as Ayurveda, a practice that flourishes even today in India. These were all exemplars of science, but modern science education in India has largely ignored these ideas and practices of earlier science.

The British and European response to the discovery of these traditions was one of skepticism and derision. But confronted with the empirical evidence of these traditions, including a living tradition of the successful medical system called Ayurveda, they took recourse to the argument that such practices in India were primarily artisanal in nature. According to them, what made an approach scientific were the notions of theory and method, which presumably these earlier traditions in Asia did not possess.[16] Thus, these discoveries were seen to be "accidental," empirical, and not a product of a "method." Similar arguments were part of the European response to Indian philosophical systems, particularly the logical tradition that was part of almost all these systems.[17] It was important to deny the capacity for

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[13] See Sarukkai (2005) for a discussion of how Indian logic shows conceptual similarities with methodologies that we would call as scientific methodology today.

[14] See Adas (1989) and Alvares (1991) for a detailed description of Indian technology.

[15] The text listing some of these results is available now with translation and with a symbolic rewriting of the text. See Sarma (2008).

[16] See Adas (1989) and Alvares (1991).

[17] See Matilal (1985), Mohanty (1992), and Sarukkai (2005) for a discussion on the nature of Indian logic and rationality.

logic to the Indians since rationality, a trait that defined the modern European mind, was a value that was used to hierarchize civilizations. European scholars took the view that Indian civilization did not develop logic and therefore did not have access to rationality.[18]

In understanding the relation between Indian culture and science education, we need to engage with the practice of science in ancient and medieval India.[19] This is not only to set right the asymmetry in invoking the ancient Greek or modern Europe in the context of science but also to begin to look at new features and characteristics of what could be called science. The only way these ideas and arguments can enter science education is through HPS. Adding the story of ancient and medieval scientific practices as part of a longer and multicultural history of science will have an immediate impact on the way students learn science. This approach should be of interest to science teachers in other countries as well. While science educators have discussed the importance and effectiveness of teaching scientific concepts through a historical trajectory, they have in general ignored the possibility of other histories of these concepts drawn from non-Western traditions. Almost all concepts such as mass, matter, energy, cause, effect, substance, chemical, and material are described in great detail in different cultures and are articulated in different ways.[20] When history of science draws only upon one historical narrative, it reinforces the myth that all seminal ideas in science (and even philosophy) occurred in the "West." But this is a limited reading of history of science itself. Thus, an encounter with the Indian context forces a change not only in science education (in terms of curriculum as well as pedagogy) but also in the mainstream history of science community. Through this intervention and broadening of their view of history of science, historians of science can actually make a stronger claim to the relevance of HPS to SE across the world.

53.5 Does Multicultural Origin of Science Matter?

In contemporary history of science, there is a strong claim to the multicultural origins of science (Bala 2006). There are some variations in this theme, but all of them agree that to claim modern science began in Europe is to ignore the many cultural influences that made this origin possible. The gist of this argument is that ideas from the Greek, Arabic, Chinese, and Indian cultures reached Europe in various ways – both in the form of texts and instruments. Europe afforded a geographical

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[18] See Ganeri (2001) for the early European response to Indian logic.

[19] See Arnold (2000) for more on medieval India. He also points to rich development in science in the Mughul period, particularly in medicine.

[20] Indian metaphysics understands some of these concepts in quite different ways compared to the modern West. For example, the mind-body duality following Descartes is not found in these schools, since mind is seen to be a species of "matter." There are many interesting theories of causation in the various schools. The point is that some of this diversity may actually be useful for alternate understanding of scientific methodology and processes.

location where all these confluences could meet and develop, and it is in this milieu that modern science originated. There are deeper undercurrents to this claim – the possibility that knowledge had actually been transmitted to Europe but which had not been acknowledged. Examples of how Copernicus drew on the Maragha school of astronomy, how Kepler depended on Chinese observations, or how the possibility that the first ideas of calculus went from Kerala in India to Europe raise troubling issues about the beginnings of modern science and their true "origin." General principles that define science such as the amalgamation of the theoretical and the experimental, following Bacon and Galileo, are principles that inform earlier intellectual traditions in India and China. As Bala points out, "solar, lunar and planetary models of al-Shatir are mathematically identical to those proposed by Copernicus some 150 years later" (ibid., p. 83). Similarly, optical revolution in Europe was influenced to a significant extent by the work of al-Haytham (Alhazen). Bala further argues that mathematization of nature – a profoundly important moment in the origin of modern science – is indebted to the "meeting in Europe of Arabic philosophy and science with Chinese mechanical discoveries" (ibid., p. 122).

In the context of SE in India, the discussion on the multicultural origins of science, derived from history of science, will have a significant impact on the reception of science by students. There are two dimensions to this reception: one is the shared cultural and national histories of science available through multicultural histories of science, and the other is the availability of shared vocabularies and practices that might make the student more "culturally comfortable" or "culturally contiguous" to science that is taught today. In almost all the textbooks of science, the heliocentric model is associated with Copernicus. Where a little history of this model is available, it often begins with Tycho Brahe and ends with Galileo. The heliocentric model is an extremely important model of science – both for the history and origin of science and also for communicating the power of science because the claim that the Earth revolves around the sun is now such a cultural truism that it is part of commonsense now.

However, this is an incomplete version of history. There is sufficient literature to illustrate how the model of Tycho Brahe was described by the Kerala mathematicians quite some time before Brahe. The modified heliocentric model developed by these astronomers/mathematicians was described in texts that were known to the Jesuits in Kerala in the early sixteenth century.[21] Whether these ideas got transmitted across continents is not really the issue. What is however at stake is the placement of these seminal ideas within the capacity of other cultures. Does this mean that an Indian student will better understand and appreciate heliocentric motion once she is taught about the contribution of the Kerala mathematicians? There are no simple answers to this question, but this question needs to be considered for it is possible that awareness of a history of "their own" scientific theories might allow students

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[21] See Bala (2006), Raju (2001), Ramasubramanian and Srinivas (2010), and Sarma (2008). See also Plofker (2009) for a detailed introduction to Indian mathematics.

to have a different stakeholdership towards that subject thereby influencing their learnability of science.

Teaching multicultural theories of the origin of science relates science and scientific ideas to subjects such as history and geography. It grounds science not only in the empirical world but also in a discursive world where it shares some common stories across disciplines. In the Indian context, one might say that the students face two kinds of alienation with respect to science: one is an experiential strangeness and the other is a cultural strangeness. An ironic illustration of this alienation lies in the history of technology. As mentioned earlier, there is a well-established scholarship now that describes the enormous technological advances of ancient Indian societies.[22] The first examples of metallurgy, including the invention of steel and zinc, were to be found in India. These processes actually found their way to England in the colonial era and catalyzed modern production of these metals. However, this rich and long history of metallurgy, chemistry, and other pioneering innovations in India and China are rarely even mentioned in science textbooks. Teaching science by drawing on multicultural origins of science is a good way to reduce the strangeness on both these counts. However, like in the case of HPS in SE, teachers have to first engage with these new histories.

Finally, we should note that introducing multicultural origins of science in SE is but one step in allowing multiple histories of science to enter the classroom and science texts. In the Indian case, there are such multiple histories available such as the subaltern histories and artisan histories. In all these alternate histories, there are some profound insights into the nature of the world and the universe, as well as important elements of the nature of enquiry, observation, and experimentation.

These arguments are but an extension of arguments in education that suggest that learning becomes easier when ideas are expressed closer to the contexts in which the children are immersed. For example, the attempt to teach abstract ideas through examples that are common to the cognitive experiences of the students is but one variation of the above arguments. What is being suggested here is that scientific ideas become more easily accepted and understood if a common history is exhibited. As a motivation, we only need to note the rich historical debates on the origin of science in Europe, a topic that has become so contentious that it inspires Dear (2005) to remark on the identity crisis confronting historians of science because of the difficulty in establishing strict boundaries that demarcate science from nonscience. The recognition of a stable subject matter for history of science has become difficult given that the "very category of "science" has become historicized – and hence very slippery" (ibid., p. 391). This observation, as well as the ones on the multicultural origins of science, should not be read as supporting the claim that "everything is a science." What it merely does is expand the space within HPS to interrogate the diverse forms of science[23] and take this into account in the larger debates in SE.

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[22] See Adas (1989), Alvares (1991), and Dharampal (2000).

[23] We should remember that the diverse forms of science are already exhibited in the contemporary typology of science. Today, science includes quite different disciplines ranging from physics, chemistry, and biology to economics, library science, management science, and so on.

53.6 Nature of Science and Science Education: Lessons from Premodern Indian Science

The above discussion is related to a more commonly discussed theme in relation to HPS, namely, the NOS debate in SE. Turner and Sullenger (1999) offer a good overview of the sociology of the NOS debate within science education. But like other reviews in this field, there is no mention of the possibility of articulating new themes in NOS that are catalyzed by non-Western philosophical traditions.

One of the important ways to argue for the relevance of NOS is to show how awareness of the process of science (e.g., as a combination of the experimental, observational, and the conceptual) adds to the students' understanding of the concepts of science. Matthews (2001) describes how the study of pendulum in a class illustrates the importance of NOS to science education. Much of the impact of NOS has been discussed within the cognitive domain. However, a major influence of NOS on science learning also has to do with various psychological aspects of learning. A robust and complex theory of the nature of science demystifies the inherent ideology of a particular image of science. An outline of how the debate on NOS can be influenced through this engagement with Indian experiences follows; how these issues can directly affect SE is, at this moment, only speculative.[24]

As discussed in an earlier section, science and technology were well-established social practices in ancient and medieval India. All philosophical traditions were fundamentally concerned with the various means of acquiring knowledge. Hence, the study of epistemology was the fundamental concern for these philosophers (Matilal 1986). Thus, it should not be surprising that much of their work impinges on philosophy of science. In exploring the nature of knowledge, extensive work was done on the nature of perception, inference, language (testimony), and other related modes of learning. The Indian theories on inference make two important contributions of relevance to this chapter. One is the five-step process of inference in the early Nyāya tradition, which basically explains one's inference to another through a process of reasoning (Matilal 1999). Let us say that one infers fire on seeing smoke. The five-step process describes how we could effectively explain why we infer fire on seeing smoke. It begins by first noting the empirical event of seeing smoke, then invokes a universal reason (where there is smoke, there is fire), then uses a common example known to the speaker and hearer (such as smoke-fire complex in a kitchen), and finally concludes that the inference of fire is indeed correct. This five-step process at one stroke combines the rhetoric of communication, the process of inference, and also the process of cognition involved in the inference. It is also a system which has

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[24] One of the sustained efforts in this direction in India is the series of conferences called epiSTEME organized by the Homi Bhabha Centre for Science Education, Mumbai. The publications of each of their conferences contribute significantly to this debate in India, although the difficulty of directly drawing on Indian intellectual traditions for science education remains.

striking parallels with the deductive-nomological model of scientific explanation (Sarukkai 2005).[25]

The second contribution to the study of inference comes from the Buddhists who offer a semiotic model of inference. They analyze the conditions that will enable one to know when a sign stands for a signified, such as smoke as a sign that stands for fire. This relation between sign and signified is also at the heart of instrumental observation in science. The way by which these Indian logicians analyze these inferences offers new ways of understanding the relation between semiotics and logic as well as between semiotics and science (a topic that has rich resonances in the interpretation of experimental results as well as in the use of mathematical writing in the sciences).[26]

There is an important lesson about NOS in these Indian approaches to inference. First of all, there is a completely different approach to the idea of "theory" in Indian thought. European scholars who encountered Indian logic found the combination of the formal and the empirical very troubling (Ganeri 2001). Similar arguments also legitimized the British appropriation of Indian technology by claiming that the Indians knew how to make steel, for example, but did not understand the theory behind it (Adas 1989; Alvares 1991). Do these alternate approaches have any implication for science and for science education today?

Any account of modern science has to engage with the idea of the theoretical. As is well known, what we call science today was referred to as natural philosophy at least till the seventeenth century. Natural philosophy was seen to be a speculative, theoretical act. The distinction of theorica/practica drawn from Greek thought was extremely influential in the way disciplines such as medicine, astronomy, and other "arts" were understood (Dear 2005, p. 393). Till the early seventeenth century, natural philosophy was immune to this distinction as it was seen to be mainly speculative philosophy with no practical applications. It was Bacon who constructed natural philosophy as a discipline which also had practical utility. Moreover, the influential distinction between mathematics and natural philosophy continued till the eighteenth century. These lead to the distinction between the categories of "pure" and "applied" in the nineteenth century which continues till today. This short historical interlude is merely to point out how such a tradition of understanding science does not occur in Indian thought. At the core of different Indian intellectual traditions there is a suspicion about such distinctions. There is no clear distinction between logic and epistemology, between metaphysics and epistemology, between ethics and epistemology, between formal and the empirical, and between mathematics and the sciences.[27] This approach to theory and practice in Indian thought is of great significance to science teaching of these subjects. For example, drawing on the unique nature of Indian mathematics – both in its empirical grounding and in its

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[25] This model of scientific explanation suggested by Hempel and Oppenheimer argues that the explanandum is a deductive conclusion from a set of premises which consist of lawlike as well as empirical statements. This structure does a similar task as the Nyāya process.

[26] For a detailed analysis of these semiotic elements, see Sarukkai (2005). See also Sarukkai (2011).

[27] See Bhattacharya (1958) and Mohanty (2002).

textual and discursive practices – might actually help address some problems of science and mathematics education.

Ayurveda, the enduring medical tradition in India, is another classic example of the inherent mix of the theoretical and the empirical. In this case, there is also a strong component of the experimental and not merely the observational. Ayurveda is a classic example of a scientific tradition which exemplifies many of the virtues of modern scientific method including observation, theory, experimentation, and intervention. Yet it is rarely taught as such to students and in school science textbooks; it is rarely mentioned even though the so-called modern (allopathic) medicine is given as an exemplar of science. Ayurveda, as a scientific practice, involves some real observational biology. Its classification of plants is exhaustive and scientific in the modern sense of botany.

What then are the implications for science teaching if such contiguous, local traditions are taught as illustrations of the nature of science? Equally importantly, how will science education in the West learn to draw on these Indian scientific traditions in their own teaching of science? What is being suggested here is that HPS' contribution to the nature of science debate has been too Eurocentric. Drawing on another history of science from another culture – one in which the idea of "science" does not exhibit the standard fault lines of theory and practice, as well as the metaphysical baggage of this distinction – might actually contribute to the development of new ideas and practices in SE.

In the Indian context, whether in philosophy, art, or mathematics, the primary emphasis is on making the theoretical always answerable to the empirical. Thus, there is no idea of pure rationalism, pure mathematics, etc., which characterize some dominant traditions of Western thought. Now this has been interpreted by some European scholars, as pointed out in the earlier sections, to suggest that Indian culture has no understanding of theoretical rationality that is often associated with science. There has also been a long colonial project of interpreting Indian culture as being primarily religious and this along with the claim that modern science begins from a conflict with the Church has led to the claim that Indian culture had no links to modern scientific thought. This myth continues in spite of a large amount of literature on these aspects – both of Indian systems and on the nature of science. In particular, history, philosophy, and sociology of science have illustrated so well the complex relationships which science has with logic, religion, method, and so on (Sarukkai 2012). But the complete absence of these disciplines in science teaching means that certain traditional ideologies about science, such as those discussed in the earlier sections, continue to be propagated in science textbooks even today in India.

The implications of drawing on these "indigenous" modes of understanding the nature of science and mathematics are many. First of all, the metaphysical foundations of these disciplines are quite different in the Indian context when compared to the Greek and the modern "West." For example, Platonism seems to be unthematized in Indian thought. Mathematics and the sciences were always empirically grounded. Since their presuppositions are different, they create the possibility of a different method of teaching science. Secondly, when science is taught along this trajectory, students begin to understand science as a social process. Now, science is dominantly understood as a packaged knowledge system which seems to have been given to us miraculously – if not by gods, then by “great scientists.” In contrast, teaching science as a social and historical process, with its own special cultural moorings, may actually interest more students in science. Drawing on Indian logic gives us new methods of communicating the practice of reason and of thinking – arguably the two most important characteristics of learning. It also illustrates the importance of rhetorical communication in matters of reason such as using the nature of evidence and reason on which to base conclusions, details of which are given later in this chapter.

There is another important aspect of NOS from these Indian traditions, which can be briefly alluded to here. This has to do with the relationship between language and science. Almost all Indian philosophical traditions were deeply concerned with the nature of language and its relation to the world and human cognition. There is a constant attempt to create languages which capture truth and knowledge – Sanskrit itself is a very good example of a semi-technical language (Staal 1995). Later philosophers of the Nyāya tradition created a modified form of Sanskrit in order to remove the ambiguities present in ordinary Sanskrit (Bhattacharyya 1987). This engagement with language is wonderfully illustrated in the ways by which mathematics gets written in prose and poetic forms. Although a very important topic, the role of language in science[28] has not been sufficiently dealt with in the HPS literature. The richness of language use in science and science learning attests to the possibilities of drawing on these rich Indian philosophies of language.

Consider the teaching of mathematics. There is a long tradition of mathematics in India, one that includes the seminal text by Āryabhaṭa called the Āryabhaṭīya. What happens when a student is also given these historical descriptions of these alternate forms of doing and writing mathematics? Here are some speculative (but hopefully reasonable) outcomes: one, the student recognizes that there are different ways of doing and describing trigonometry – this automatically decreases the anxiety of doing something the right way or following the “right” method; two, she would recognize that such ideas were not really alien to the larger cultural world which she belonged to; and three, she might even recognize (with some help from the teacher) that mathematics has an interesting relationship with language, perhaps a language which she might be “culturally familiar” with. Such approaches might help in getting rid of the perennial and enduring fear of symbolism that seems to strike school children across the world.

53.7 Constructivism and Indian Philosophy

There is another characteristic of Indian philosophical traditions that may have a direct impact on SE. Indian philosophies have a unique way of describing the human interaction with the world. They, without significant exception, describe these

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[28] See Sarukkai (2002).

interactions in terms of cognitive episodes.[29] Thus, perception is defined in terms of cognitive states that occur when somebody sees or perceives something. Inference is also defined in terms of cognitive states. So a description of a process is through a series of cognitive states. This mode of cognitive description for processes including that of logic is a good model for teaching subjects such as logic, mathematics, and science. The example discussed below will illustrate how this method of teaching science has metaphysical overlaps with constructivism while at the same time negating the excessive subjectivities which are potentially inherent in constructivism.

Consider a classic example of inference from Indian logic, the inference of fire on a hill from seeing smoke on the hill. Almost all schools of Indian philosophy considered inference as one of the valid means of knowing and so expended a great deal of effort in trying to describe the processes of valid inference. An example of valid inference would be the inference of fire from seeing smoke, but how can we be certain of this inference? Indian logic, pioneers of which include the Nyāya school and the Buddhists, described the inferential mechanism through a series of cognitive processes. For example, one such description followed by Nyāya is as follows: when a person sees smoke, there is a cognitive state corresponding to that perception. This state is followed by another state in which she remembers a universal rule – the principle or the reason for the inference – that where there is smoke there is fire. This cognitive state is followed by the next one which, through this rule, recognizes the smoke as standing for fire. This leads to a cognitive state which is the inferentially knowing state that there is fire in the hill.

Many Western scholars were puzzled at the cognitive descriptions of the logical process of inference and thus concluded that Indian logicians were committing the fallacy of psychologism.[30] This is a common mistake in responses to cognitive descriptions and is catalyzed by the belief that descriptions of the world should refer entirely to terms of the world and not to terms of personal experiences of the world. But what is intriguing is that the logical school, Nyāya, is a realist one. They do not in any way accept that the perception of smoke and the inference of fire are personal, subjective ones. They are committed to a realist metaphysics which acknowledges the "reality" of the smoke and fire. Yet, they are also committed to the reality of cognitive states, and the challenge in this philosophical approach is to retain the descriptive power of cognitive states and yet retain the possibility of a common reality accessible to the many cognitive subjects. It is this effort that really distinguishes and explains the unique nature of Indian philosophical discourses. As Mohanty points out, these philosophers do not end up with psychologism because "a cognition has a logical structure which allows for being exemplified in another numerically distinct episode belonging to another ego and/or another temporal location" (Mohanty 2010, p. 437).

Why would this matter to constructivism? While constructivism seems to be a popular movement in science education, there have also been strong critiques. For example, Matthews (2002) argues that although constructivism has been very

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[29] See Matilal (1986) and Mohanty (1992, pp. 100–132 in particular).

[30] See Mohanty (1992) for a discussion on this theme.

popular in SE, there are nevertheless many points of disagreement and worry. He also notes that there are a variety of ways in which constructivism is invoked in SE, namely, constructivism as a theory of learning, teaching, education, cognition, personal knowledge, scientific knowledge, educational ethics and politics, and worldview (ibid., p. 124). In Matthews (2004, p. 107), he lists various claims of constructivism such as the lack of objective knowledge of reality and experience as the primary basis of scientific knowledge.

It seems to be the case that many of the conclusions of constructivism are grounded in the experiential mode and the cognitive primacy of learning, which situates knowledge/truth within the learner. Dominant analytical traditions in Western philosophy do not have the wherewithal to cope with this form of grounding. (There are other traditions which offer different approaches to "extracting" the objective from the subjective – Husserlian phenomenology is one such.) In Indian philosophy, this grounding in the cognitive states of the experience is a given for all processes related to knowledge of something real. But this does not reduce these descriptions to a naïve form of psychologism and individual subjectivities. That is, the mere fact of a cognitive description of the learning process, *in itself*, does not make the whole process subjective. In other words, there is really nothing in the metaphysics of constructivism (when viewed from the Nyāya perspective or the phenomenological perspective) that necessitates the shift to claims that all truth is within the learner and not "outside," that scientific knowledge and truth are all relative to each learner, and so on. The conclusion that constructivism is necessarily subjective is based on a flawed understanding of the nature of subjectivity as well as of the nature of cognitive states. The Indian logicians' analysis of inference shows how it is possible to hold onto a robust realism while at the same time accepting the primacy of individual cognitive processes of perceiving, inferring, and learning. Through this approach, there is a good possibility to marry constructivism with realism; this can be one example of "using" Indian philosophy for a contemporary debate in SE.

53.8 Rhetoric and Methods of Teaching

It would not be an exaggeration to say that rote education is seen as the bane of Indian education. Whether in newspaper reports or the last National Curriculum Framework, there are repeated references to the effect of rote learning and the prevalence of this mode in Indian schools and colleges. This mode of learning is particularly problematical for science education since rote education is often contrasted with critical and creative thinking, and problem-solving, which are the hallmarks of a "good" science education.

It is a mystery as to why the Indian educational system is saddled with such a strong component of rote learning. Like many other ancient cultures, there is a strong sense of orality in Indian culture.[31] Texts are memorized and recited. Even

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[31] See Fuller (2001) for an interesting case study on orality.

when Sanskrit is taught today by traditionalists, the most important component of teaching that language lies in pronunciation. For a long time, texts were transmitted entirely through oral means, and this meant that the language as well as strategies of memorizing made it easier for oral transmission. It is interesting to note how even philosophy and mathematics texts were written in poetic form, thus making them amenable to an oral discourse. For some, this cultural practice of orality seems to have transformed into rote learning in contemporary education.

Although one might be tempted to ascribe the prevalence of rote learning to ancient cultural practices (such as language learning and oral transmission of texts – none of which necessarily implies rote learning), it is the educational policies and practices that are obviously a bigger culprit.[32] The most enduring reason for the continuation of this mode of learning is the examination system. Every year, one only has to see newspaper reports during exams and during admissions to read about the menace of "rote learning."[33] Even the government bodies and their representatives keep bemoaning this characteristic of Indian education. One of the most influential documents on education and education policies in India, the National Curriculum Framework 2005, notes the problem of rote learning and the means to curtail it. The National Curriculum Framework for Teacher Education 2009/2010, makes pointed references to the problem of rote education.[34] Many alternate private schools promote their system by claiming that they teach critical and creative thinking as against rote learning, which they claim is endemic to public education.

This entry into the discussion on rote learning is to offer a perspective from Indian philosophical and intellectual traditions on critical thinking. Critical, reflective thinking is often seen as the antidote to rote learning. The inculcation of these virtues is fundamentally the task of philosophy, and it is here that HPS becomes immediately relevant to SE. Philosophers over the ages have viewed philosophy as being concerned fundamentally with the nature and processes of thinking. It is impossible to engage with philosophy and not be involved in modes of reflection and thought. In the Indian context, there is an interesting practice related to critical thinking. All Indian philosophical traditions use "debate" as their fundamental rhetorical strategy. In these traditions, debate is classified into different types, and a student in these schools has to master these debating strategies. The influence of debate is so integral to Indian philosophies that even texts follow the form of a debate. Thus, a standard philosophical text will first describe the opponent's view and then counter it step by step. Almost all seminal philosophical texts follow this method.

Debate is an important rhetorical strategy. It is a great training for critical thinking and a powerful pedagogical tool. A good illustration of this can be found in the practices of Buddhist monastic training even today, where the students are trained not only in the theories of debate but also in the "performance" of debate. One can

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[32] See Chitnis (1993) for an analysis of the changes needed in the Indian education system.

[33] See, for example, TOI http://articles.timesofindia.indiatimes.com/2011-06-19/education/29676322_1_high-scorers-evaluation-board-examination.

[34] See http://www.ncte-india.org/publicnotice/NCFTE_2010.pdf.

see these forms of “performative” debates between different schools in Buddhism in many monastic schools.

Debate is the founding principle of all Indian philosophical traditions (Matilal 1999). Logic in India arises out of debate. Every philosophical system classifies the various forms of debates; the intellectual battles between different schools were to be won on the court of debate. Interesting historical anecdotes about debates are prevalent in narratives about the different philosophical traditions. Debates were a common occurrence in the courts of kings, and there were well-established mechanisms for judging the winner of these debates. Debate was the forerunner not only of Indian logic but also of rhetoric and communication praxis.

As Matilal points out, the Buddhist canons of debate illustrated fundamental logical principles such as modus ponens and modus tollens. Debates themselves were classified into “good” and “bad” debates or “amicable” and “hostile.” Nyāya classifies debates into three types: one between a student and teacher, whereas the other two are primarily “hostile” in that their basic aim is about being victorious in the debate. The good or “honest” debate between a student and teacher is characterized by the following properties:

1. Establishment (of the thesis) and refutation (of the counter-thesis) should be based upon adequate evidence or means for knowledge *(pramāna)* as well as upon (proper) “hypothetical” or “indirect” reasoning *(tarka).*
2. The conclusion should not entail contradiction with any tenet or accepted doctrine *(siddhānta).*
3. Each side should use the well-known five steps of the demonstration of an argument explicitly.
4. They should clearly recognize a thesis to be defended and a counter thesis to be refuted. (Matilal 1999, p. 45).

All educational instruction followed these steps. These not only establish a communicative mode to discuss and analyze propositions, they are also essential to what we call as critical thinking today. Nyāya also has a classification of the other two kinds of “hostile” debates and lists in great detail the elements constituting these kinds of debates. Since victory (by any means) is the goal in these “hostile” debates, a debater can use the following strategies: quibbling, illegitimate rejoinders, and clinchers. Moreover, there is an extensive classification of the types of quibbling (3), illegitimate rejoinders (24), and clinchers (22) (ibid., p. 47). It is this complex system of argumentation that is at the heart of Indian rationality, and interestingly, it has pedagogy at its center. An illustration of these methods for students will enrich not only science education but also critical thinking and communicative processes in all aspects of education.

Although such practices have not become part of education in India, they can nevertheless be effectively used to teach critical thinking. The performative tradition of debates in Buddhist monasteries illustrates one way of incorporating the skill of critical thinking as part of educational practice. In schools today, such methods can easily be adapted. Here is one possible way to do this. The students will debate a particular hypothesis but will have to follow the rules of debate as enumerated in these philosophical traditions. For example, consider a simple thesis: all matter is made up of atoms. How will the students debate this question? What kind of rules of debate will they invoke? The rules of debate drawn from these Indian traditions of debate can be given to the students, and they can be asked to follow these rules in the course of the debate. For example, the Nyāya describe many kinds of checks, since for them, "debate was like a game of chess, in that the opponent and the proponent make their moves and at the end there is a clincher, when one side will be checkmated" (Matilal 1999, p. 81). They list "twenty-two types of defeat-situations," which are arguments which will show the opponent's arguments to be wrong. One such is abandoning the thesis in the course of argument; thus, if a student suddenly invokes the existence of space and time while debating the existence of atoms, she could be countered by saying that she has abandoned the thesis of the original debate. Some of the other clinchers against the opponent include "irrelevant speech," "incomprehensible speech," "adding unnecessary steps," and "repetition." (Examples of using jargon or dropping names of scientists to justify the thesis can fall under one of these categories.) Students trained in such manual of debates will be able to analyze what they hear and evaluate the faults of arguments based on specific categories. One can modify these rules for the present-day context. The bottom line is that such exercises in thinking and debating can enhance the skills of learning and thinking in a profound manner and there is much that the rational traditions of India and China, for example, can contribute to this project. Such an exercise will be of relevance to students across cultures.

53.9 Conclusion

This chapter explored new ways of engaging with HPS in the context of SE with a specific focus on Indian experiences of science and science education. One of the challenges to science education in India lies in the contestation about the very notion of science. Given that the Indian civilization (like other non-Western ones) had a long engagement with themes and practices of what seems like science, it is necessary to understand why science education in India is almost completely silent about engaging with these traditions. Thus, the sections on multicultural origins of science and the nature of science debate discuss the ramifications of understanding these practices as science and also the importance of including them in the curricula. One of the consequences of including them in the curricula is that students begin to develop a sense of ownership and confidence with respect to scientific thinking and practice. This step allows the possibility of broadening our understanding of science without also, at the same time, claiming that everything is science.

The two sections on constructivism and rhetoric are attempts to illustrate how one can draw on alternate philosophies that can contribute to some of the important contemporary debates in science education. By doing so, attention is also drawn to the exclusiveness of the global HPS community, which has steadfastly ignored the historical and philosophical contributions of the non-West. Hopefully, this chapter can partly loosen the intellectual strings of this community and through it that of the community of science educationists.

This chapter does not address issues related to learning scientific content and the philosophical issues associated with it. This is primarily because of the India centricity of this chapter. Much of the debate may seem unnecessarily focused on certain aspects of earlier science or on cultural implications of ignoring non-Western traditions. However, as argued in this chapter, it may not be desirable to so completely demarcate the learning of content from the learning of the concept and methodologies of science.

In drawing on the earlier intellectual traditions, some contemporary contributions have been kept out of the purview of this chapter. In particular, there is no engagement with two influential thinkers/educationists of contemporary India, Gandhi and Tagore. Both of them were deeply interested in education and both of them had deep insights into the nature of education. They are of particular interest because of their attempts to fundamentally integrate educational practices and ethics. Gandhi (1951, 1953) proposed his ideas of education as part of a new system called the *Nai Talim*. This schooling is radically different from mainstream, government-supported education system. It is important to realize that these approaches emphasized fundamental ethical principles as being integral to the education process, content, and pedagogy. These principles include social justice and nonviolence, the defining principles for Gandhi. Gandhi's views on education make ethical action integral to the process of learning; it is not possible to divorce the content of what we learn from the set of acts to which ethics is applicable. That is, the Gandhian challenge is to make the ethical an integral part of the cognitive. But the insights from Gandhi and Tagore are not specific to science education, and hence, this chapter concentrates on alternate engagements between HPS and SE.

Finally, is it important to take into account other HPS traditions in SE? The unequivocal answer to this question has to be in the affirmative. The major reason is that many of these beliefs about science which are at the foundation of curricula and teaching of science are just plainly mistaken. They represent a particular rhetoric of science, and this rhetoric is abundant in science texts. Those who claim that texts are only about content of science and nothing else are only echoing a particular rhetoric of science which is itself based on some specific history and philosophy of science. These particular views have been challenged enough in HPS literature. Ironically, the alternate formulations related to science are not just from non-Western cultures. There is absence of many small traditions within Europe itself, those which have not found their way into these science texts.

This is ironical given that HPS has generated enough material, especially in recent times. This is especially true of history of science which has been able to engage far more deeply with multicultural and global histories of science. They have also been able to disentangle the many small science traditions within Europe. However, the scientific community not only ignores these narratives but many times is also inimical towards them. The question that science educationists should ask is this: Can they afford to similarly ignore these contributions in teaching science? Should they be subservient to the dominant ideologies of the mainstream scientists? Most importantly, can SE be independent of the ideology of science propagated by the scientists, an ideology which is deeply encoded in the content of science in various ways?

The enduring question as to whether students will do better in science if they are taught the history and philosophy of science has to be addressed. Rather than take this position, it is more useful – at this juncture – to emphasize the importance of HPS to science teachers. The question that is relevant now is whether teachers will be able to teach science better if they are exposed to HPS. There are good reasons to believe that the answer to this question is an unqualified yes.

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Chapter 54
Historical Interactions Between Judaism and Science and Their Influence on Science Teaching and Learning

Jeff Dodick and Raphael B. Shuchat

54.1 Introduction

To the eye of the layman, Jews and science seem to have a definite association. To support such claims, some point to the large number of Jews who have won Nobel prizes in the sciences and Fields Medals in mathematics (Efron 2007) and to the numerous scientists of Jewish origin teaching at US-based universities (Lipsett and Raab 1995). However, as Efron (2007, p. 2) rightly points out, statistics such as these are "crude" given that most practicing scientists of Jewish origin are not usually guided by the tenets of Judaism, so it is a misconception to argue that Judaism, in of itself, is the reason for these scientists' interest or even association with their respective fields. The question, therefore, is what does Judaism have to say about science?

In this chapter, we will examine the historical and philosophical meeting between Judaism and science and how it in turn has influenced the teaching and learning of science. In so doing, we will be asking the following questions: How has the relationship between science and Judaism developed over history? What are the philosophical approaches that have developed in Judaism for dealing with the challenges that science sometimes poses? What are the subjects of science that most specifically create such challenges for Judaism? And most important for this book chapter: How has this meeting between Judaism and science affected the teaching and learning of science?

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In order to answers these questions, we will first provide a brief review of the historical interactions between Judaism and science, the goal being to examine the major trends that have developed through time. Based on these historical trends, we will define the major philosophical approaches (or models) that have developed within Judaism for dealing with the possible challenges posed by the domain of science. By understanding how Jewish thinkers have coped with these perceived challenges, it will be possible to analyze how this relationship has affected the modern science education system (specifically in Israel or in educational systems, outside of Israel, where Jews are the majority). The answers we provide to these questions may serve as a guide towards improving the quality of science education in Jewish school systems around the world.

54.2 Judaism and Science: A Historical Overview

To give a comprehensive analysis of the interactions of Judaism with science over the ages is beyond the scope of such a short chapter. Instead, as this chapter is found within a book on the role of history and philosophy of science in science teaching, we specifically define those interactions between Judaism and science that have relevance for science teaching. In this way, we will be better positioned to understand how Jewish teachers and students of science understand and even cope with potential conflicts between the two perspectives.

In order to understand the Jewish position on science, we will begin by defining what we mean by science for this chapter. In early Western-Greek culture, the philosopher was de facto the scientist: the physicist, the astronomer, and the medical doctor. Therefore, in order to gain a broad understanding of Judaism and science throughout the ages, we have to relate to three categories which characterize the scientific enterprise over the ages and their interface with Judaism: (1) technology, (2) exact sciences (most notably, astronomy and biology[1]), and (3) natural philosophy in antiquity. In the modern era, with the separation of science and philosophy, we have to relate as well to the fields of (4) cosmology and cosmogony (most notably, evolution). The first two categories represent the products

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[1] In this historical discussion, we address, among other things, the simple question of the rejection or the acceptance of biology, in general, as a science in antiquity. In the twentieth century, the issue of biomedical ethics has developed tremendously and so have the discussions concerning medical ethics and Jewish law. Much has been written about, including organ transplants and the definition of death, fertility issues, machines for prolonging life and disconnecting terminal patients from them, and cloning. Steinberg (2003) wrote an *Encyclopaedia of Jewish Medical Ethics*; moreover, *Shaare Zedek Hospital* in Israel has a journal dealing with such issues titled, *Asiya*, and much discussion can be found in legal journals as well. However, there are two reasons why this issue is not part of this short chapter: First, the research is all done on the graduate level and by experts and does not find its way to the classroom at the high school or even undergraduate level. Secondly, this issue has nothing to do with acceptance of biology or medicine and how it effects education, but very specific ethical issues within that realm.

of human reason and the third and forth, human speculation and inquiry about life and the (formation of the) universe.

To understand any Biblical Jewish position, we must use the oral tradition, or as it is also known, the rabbinic tradition, to interpret the Masoretic text of the Bible; this rabbinic tradition commences with the Talmudic and Midrashic period (100 BCE–600 CE) and represents the classical period of Jewish literature.[2]

54.2.1 Technology

In the Book of Genesis, Noah, was so named by his father Lemekh to mean: "This one shall comfort us for our work and the toil of our hands because of the ground which the Lord has cursed" (Genesis 5, 29). The curse of the ground is mentioned twice before in Genesis: the first time as part of Adam's punishment for partaking of the Tree of Knowledge (Genesis 3, 19) and the second time when Cain kills Abel (Genesis 4, 11–12). The rabbinic understanding of the curse was that the land would not produce food so easily, so man would have to sweat and toil to produce something which is not just thorns and thistles. However, this curse is not insurmountable; it takes human initiative and cooperation to overcome it. The Midrash (Tanhuma Genesis, 11) writes that until Noah was born, one planted wheat and barley but harvested mostly thorns. After Noah was born, "They harvested that which they had planted; not only that, but until Noah they did the work by hand. [However, after] Noah was born he invented ploughs, scythes, and shovels and all their work tools" (Poupko, 1990).

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[2] By necessity, we focus on primary sources of the Jewish literary tradition, such as the Bible (the Masoretic text), the Talmud (Preisler & Havlin, 1998) and the Midrash, and their interpretations. We do so because it is these source texts and their interpretations that have been used authoritatively by Jewish thinkers, and in addition it is these texts which have been used for coping with different scientific positions. In turn, this has affected the modern science education curricula in many Jewish school systems. The Talmud is the authoritative body of Jewish law and lore accumulated over a period of six centuries (c.100 BCE–c.500 CE) in both Israel and Babylonia. The Talmud has two components: the Mishnah (Kehati, 1991), the first written compendium of Judaism's Oral Law redacted by Rabbi Judah the Prince in 200 CE, and the Gemara, an in-depth discussion of the theoretical base of the laws of the Mishnah. In addition, the Gemara includes nonlegal discussions and interpretations of Biblical texts called Aggadah as well as stories with moral implications to human behavior. The Gemara written in Babylonia is the more popular corpus and is also referred to as the Babylonian Talmud. There was a parallel Gemara written in Palestine, and it is referred to as the Palestinian or the Jerusalem Talmud (Rozenboim 2010). If "Jerusalem Talmud" is not mentioned by name in the references in this chapter, then one can assume that the Babylonian Talmud is the version being referenced. Midrashim (pl.) are rabbinic interpretations of the Hebrew Bible consisting of homily and exegesis, on both its legal ramifications and its lore. Much of the Midrashic teachings are attributed to the Tannaim (rabbinical scholars of the period of the Mishnah who lived between 100 BCE and 200 CE). Individual Midrashic commentaries continued to be composed by rabbis after 200 CE until the Middle Ages. The Talmudic and Midrashic texts are seen as the classical period of Judaism in which the oral traditions and interpretations were put to text. This literature is referred to as classical rabbinic (or *Hazal* in Hebrew) literature. All denominations of Judaism are in a dialogue with this classical literature whether they see it as authoritative (as does Orthodox Judaism) or not (as does Reform Judaism).

For the rabbinic mind, human ingenuity and the technology it produced is not only a positive thing, but it is how humankind is expected to overcome “the curse of the ground.” Instead of taking a passive position of accepting a Divine punishment, the rabbinic literature saw this “curse of the ground” as something that humankind brought about through misguided human behavior and therefore had become an issue that had to be resolved. This is comparable with the Biblical story of Moses breaking the tablets of the law after which God told him to make new ones. The idea of fixing what you break is how the rabbis of the Talmudic period interpreted this story. The resultant technology was and is the human attempt to rectify the flaws of nature caused by their own wrong actions.

A second way of viewing technology (and science) is from a practical point of view: providing one with the practical means to have an occupation. The Talmud (Makkot, 8b) says that it is incumbent upon a father to teach his son an occupation. Thus, the rabbis learned from the verse “And you shall live by them” (Deuteronomy 30, 19) that one may take time away from Torah study to study an occupation (Jerusalem Talmud, Peah 1, 1).

This second approach is also reflected in the famous debate between Rabbi Ishmael and Rabbi Simeon Bar Yohai, in which Rabbi Ishmael said that one must take off time from Torah study for a livelihood, whereas Simeon Bar Yochai thought that one should strive to devote all one’s time to Torah (Talmud Brakhot, 36). The Talmud, however, preferred the view of Rabbi Ishmael finding it more practical and applicable. From the Biblical period until modern times, Jewish religious authority has largely remained positive towards the role of technology in society.[3]

54.2.2 Exact Sciences

The Talmud did not limit science’s role to the practical task of insuring one’s livelihood. Exact sciences, such as astronomy, were seen as bringing one to recognize the wonders of God’s world, as seen by the Talmudic statement:

> Rabbi Joshua Ben Pazi in the name of Bar Kapara said: anyone who can calculate the seasons and the astral [movements of the heavens] and does not, about him the verse says: ‘and the acts of God he does not behold and the works of His hands they did not see’ (Isaiah 5, 12). Rabbi Samuel Ben Nahmani said: How do I know that it is a mitzvah [a Divine commandment] for one to calculate seasons and astral [movements]? For it says: ‘For you shall keep and do [these commandments] for this is your wisdom and knowledge in the eyes of the nations (Deuteronomy 4, 6). Which wisdom is considered by the nations? This is the calculations of seasons and astral [movements] (Talmud Shabbat, 75a).

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[3] In recent times, members of the ultra-Orthodox camp have raised concerns over the access that some computer technology gives to the media that is not in accord with their (Jewish) philosophy. As an example, some 40,000 ultra-Orthodox, US-based Jews attended a meeting at Citi Field (in New York, NY) to hear lectures about the dangers of the Internet (Grynbaum 2012). Similarly, in Israel, public calls are sometimes made to ban home computers in ultra-Orthodox communities due to their “spiritual dangers” (Ettinger 2007).

Rabbi Samuel Edeles (known as Maharsha), the sixteenth-century Biblical commentator, argued that this rabbinic statement is not speaking about calculating the Jewish calendar, since this is a calculation by the moon, but rather we are speaking here of the mathematical calculation of the movements of the heavenly bodies. Thus, Rabbi Josef Karo (2009) in his *Code of Jewish Law* (published 1565) allows one to look into an astrolabe on the Sabbath since Rabbi Karo understood that there is a rabbinic ordinance to study the heavens.

Both of these rabbis based their opinions on the rabbis of the Talmud who held scholars of astronomy in great esteem and had no problem admitting a mistake if proven wrong by non-Jewish scientists in this issue (Talmud Pesahim, 94b). In general the feeling was that there was wisdom to be gained from the scholars of the nations in this field, as the rabbinic dictum states: "If they tell you there is wisdom among the nations, believe them" (Midrash Rabbah Eikhah, 2, 17) (Freedman & Simon, 1939).

Aside from the high regard, the rabbis had for astronomy, the relation to the exact sciences was seen in quite a practical sense, similar to the attitudes towards technology. In the area of biology, we have a few sources for the study of zoology or botany in order to better understand the commandments. The Talmud states that Rav, the third-century head of the Talmudic academy in Sura, Babylonia, spent 18 years with shepherds in order to be able to differentiate between temporary and permanent wounds in animals. This he did to identify which animal qualified as a first born (sacrifice) for the Temple (Talmud Sanhedrin, 5b).

The students of Rabbi Ishmael dissected the dead body of a criminal to understand issues of purity and non-purity (Talmud Bekhorot, 45a). Again, the Talmud accepts the opinion of non-Jewish botanists when deciding an issue concerning the agricultural laws; its regard for the science of biology can be seen from the very fact that it allows one to go to a physician claiming that medicine is a legitimate science and furthermore claims that a doctor who does not charge for his skills is probably not worth seeing (Talmud Bava Kama, 85a).

54.2.3 Philosophy

In order to correctly understand the rabbinic attitude towards general knowledge, one (also) needs to understand the rabbinic attitude towards philosophy, especially Greek philosophy, which was the forerunner of scientific knowledge in the West; and in order to understand their attitude towards philosophy, it is important to introduce the subject with a brief discussion of the Talmud's attitude to Greek culture, as Greece was the birthplace of philosophy.

In this discussion we differentiate between two issues: Greek language on the one hand and Greek philosophy on the other. The Mishnah (Megilla 1, 9) states that Rabbi Gamliel permitted the translation of the Torah from Hebrew into Greek. In the Talmud, Bar Kapara added that speaking Greek was appropriate for a Jew since the beauty of Jephet (father of *Yavan* in Genesis 10,2 which is the Hebrew name for Greece) should be in "the tents of Shem" (i.e., the Jewish people) (Jerusalem Talmud Megilla, 1, 9).

Rabbi Simeon Ben Gamliel claimed that only Greek could capture the meaning of the Torah in translation (Jerusalem Talmud Megilla, 1, 9).

Despite the Talmud's positive attitude towards the Greek language (and the exact sciences) it saw the Greek use of verbal intimation negative light but was generally silent about Greek philosophy (See *Hokhma Yevanit* in Zevin (1963)). In the post-Talnudic period Greek philosophy was an issue debated for centuries among Jewish thinkers that set the tone for some of the modern Jewish attitudes towards philosophy and science.

Rabbi Hai Gaon of eighth-century Babylonia saw Greek philosophy as something which could sway one from the path of truth. Saadiah Gaon (882–942 CE), however, embraced the Islamic Philosophy of the Kalam,[4] which was strongly based on the Greek philosophical model, and was well versed in the sciences of his day. Isaac Israeli (855–955 CE) in Kairouan (modern Tunisia) also drew heavily on the philosophy and science of his day.

In Spain, the attitude of most rabbinic figures began with the acceptance of the value of Greek philosophy. Solomon Ibn Gabirol (1020–1057 CE) took a neoplatonic stance in his *Fons Vitae* (the Latin edition of what has been shown to be the original *Mekor Hayim – Source of life*) as well in his classic poem *Keter Malkhut* (*The Crown of the King*). Abraham Ibn Daud (1110–1180 CE) wrote an astronomical work and was the first to create a Jewish philosophical work based on the writings of Aristotle, titled *Emunah Ramah* (*The Sublime Faith*). Bahya Ibn Paquda, in the late eleventh century saw the study of Greek philosophy as an important tool for understanding nature and metaphysics incorporating these ideas in his *Duties of the Heart* (Ibn Paquda 1970). Abraham Bar-Hiyya (1070–1136 CE) embraced Aristotelian thinking openly in his *Higayon Henefesh* (*Meditation of the Soul*) and wrote works on astronomy, mathematics, and geometry (Bar-Hiyya 1968). Similarly, Abraham Ibn Ezra (1089–1164 CE) incorporated Aristotelian ideas and astronomy into his Torah commentary. He wrote a work entitled *Lukhot* (*Tables*) entailing astronomical tables and wrote a work on the astrolabe entitled *Keli Nehoshet* (*The Copper Instrument*) as well as *Yesod Mispar* (*Basic Numbers*) on arithmetic.

Maimonides (1135–1204 CE) was an avid believer in the importance of studying Greek philosophy and science and formulated in his *Commentary on the Mishnah*, the famous statement: "Accept truth from whoever offers it" (Maimon 1961). This echoes the (previously discussed) Talmudic respect for all knowledge, even that which originates outside the Jewish world. In addition to discussing issues of Greek philosophy and cosmology in his philosophic work, *Guide for the Perplexed* (Maimon 1956), Maimonides even incorporates ideas on cosmology into the first volume of his Halakhic[5] work, the *Mishneh Torah* (*Repetition of the Torah*) (Maimon 1987). Maimonides saw human reason and faith as inseparable. After all, if God created

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[4] Kalam is an Islamic school of philosophy that seeks theological principles through dialectic; it flourished in what is today modern Iraq, from the eighth to tenth century CE (Wolfson 1976).

[5] Halakha is the collective body of Jewish religious law, including Biblical law and later Talmudic and rabbinic law, as well as customs and traditions. Judaism classically draws no distinction in its laws between religious and ostensibly nonreligious life. Hence, Halakha guides not only Jewish religious practices and beliefs but also numerous aspects of day-to-day life.

humankind with the faculty for reason, then it cannot be that this God-given gift is at odds with revelation. The faculty of human reason is the "image of God" through which He created us (*Guide for the Perplexed*, I, I). Therefore, we need to use this faculty to understand revelation correctly. The need for harmony between reason and revelation, he states clearly: "We always attempt to integrate Torah and reason, and therefore will always explain issues (of faith) from a natural point of view. Only that which is clearly described as a miracle (by the Bible) without any other possible explanation, will we grant it the name of miracle" (as cited by Shilat 1995). Therefore, in issues of science and philosophy, Maimonides goes to great lengths to demonstrate how the scientific thinking of his day is in total harmony with Jewish faith.

Even with the difficult issue of Aristotle's theory of the eternity of the universe, which appears totally opposed to the Biblical notion of creation, Maimonides defends the (Biblical) act of creation by using Aristotelian logic and arguments from nature (*Guide for the Perplexed* 2, 13–32). The place of logic is so important in Maimonides thinking that he argued that logical deductions from revelation are part of the original intention of the revelation (*Guide for the Perplexed* 3, introduction); therefore, revelation and reason can never contradict each other. Maimonides believed in the inseparability of revelation and reason (and its derivative, science). This is best demonstrated by his statement that "if he would have been convinced that science had proven that the earth was created differently than our understanding of the Biblical text, he would have had no problem reinterpreting Genesis 1, 1" (based on *Guide For the Perplexed* 2, 25 as cited by Sacks (2011, pp. 219–220)).

The philosopher Gersonides (1288–1344 CE) accepted the Aristotelian ideas as filtered through Islamic philosophy and was an avid student of the sciences himself writing on arithmetic, geometry, trigonometry, and astronomy (Touati and Goldstein 2007). He is said to have invented a marine navigational tool called Jacob's ladder (Stanford Encyclopedia of Philosophy, http://plato.stanford.edu/entries/gersonides).

Even Judah Halevi (1075–1141 CE) who claimed in his *Kuzari* that philosophy was limited in its ability to prove religious belief was still well-versed in philosophy and the sciences (Halevi 1998). In addition, the Raavad of Posquieres, in the twelfth century, who was a contemporary of, a commentator on, and fierce opponent of Maimonides, is still quite silent concerning Maimonides' embrace of philosophy. In addition, Nahmanides (1194–1270 CE) despite his leaning towards Kabbalah, defended the study of the sciences and Maimonides' *Guide to the Perplexed* in face of French rabbinic opposition (Shavel 1963).

In general, the entire Spanish era (900–1391 CE), prior to the inquisition was an age of acculturation in which rabbis openly embraced Western thought and culture while remaining faithful to their religious beliefs. It was also the most creative period of religious philosophy in which the three monotheistic religions, Judaism, Christianity, and Islam, stood side by side on the Iberian Peninsula. Despite any ongoing political struggle, the thinkers of all three religions openly borrowed ideas from each other in the common battle against problems arising from Aristotelian thinking.

Maimonides borrowed ideas from Al-Farabi and Avicenna. Gersonides borrowed openly from Averroes and Al-Farabi and Thomas Aquinas borrowed openly from Maimonides and Al-Farabi. In fact, the common front and common issues of the three religions were so vast that the Jewish philosopher Ibn Gabirol's book, *Mekor*

Hayim (*Source of Life*), translated into Latin, was mistakenly thought to be the product of an Arab-Christian scholastic philosopher by the name of Avicebron until the Hebrew original was discovered in 1846 by Solomon Munk.

In general, as Shuchat (2008) noted, Jewish philosophy evolved when two events occurred: (1) a meeting between Judaism and Western culture took place and (2) a period in which the Jewish community enjoyed at least minimal civil rights as a minority. This occurred during three time periods: (A) the Hellenistic period from about the second century BCE in Israel and Egypt until the end of the revolt against the Roman empire in 115 CE in Alexandria; (B) the Muslim period, from the eighth century until the expulsion of Jews from Spain in 1492; and (C) the modern period, from the emancipation of the late eighteenth century until today.

In these three periods Jews experienced both Western culture and felt accepted enough to ask themselves how their neighbors saw them and took interest in the surrounding culture and thought. In the interim periods, where the Jews of the Western world did not enjoy these rights, they usually limited their study to Jewish legal writings and Kabbalah.[6]

54.2.3.1 The Opposition to Philosophy

The controversy over Maimonides writings saw the growth of an anti-philosophical movement in Provence and Spain. The Maimonidean controversy began during Maimonides' lifetime but turned into an anti-rationalist debate only in its second stage (1230–1235 CE). Solomon B. Abraham of Montpellier, David B. Saul, and Rabbi Jonah Gerondi led the anti-philosophy movement in 1232 CE. Their argument seems to have been more that the Jewish philosophers were compromising on the observance of the law and allegorizing scripture and Biblical miracles, than an attack on philosophy per se. With the burning of Maimonides books by the church in 1232 CE, the shock brought Rabbi Jonah Gerondi to retract and the controversy ended (Ben Sasson et al. 2007).

The third stage of the controversy (1288–1290 CE) was short lived, but the fourth and final controversy (1300–1306 CE) seems to have erupted again due to renewed allegations that the rationalists gave allegorical interpretations of the Bible, were lax in observance of the law, and denied Biblical miracles.

Rabbi Moses Aba Mari Astruc of Lunel persuaded Rabbi Solomon Ben Adret (also known as Rashba) to join forces. The Rashba was willing only to ban the study of philosophy or the natural sciences before the age of 25 (Ben Adret 2000).

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[6] Kabbalah (literally "receiving") is a discipline and school of thought discussing the mystical aspects of Judaism. It is a set of esoteric teachings meant to define the inner meaning of both the Bible and the traditional rabbinic literature (including Midrash and Talmud) as well as to explain the significance of Jewish religious observances in light of the inner soul and upper spiritual worlds. The term Kabbalah, meaning Jewish mysticism, is a term from the twelfth century CE and afterwards. However, Jewish mystical texts date back to at least the second temple period if not earlier. The best-known Kabbalistic work is the book of Zohar or more correctly Zoharic literature, which first appeared in Spain in the late thirteenth century (Dodick et al. 2010).

However, even Rashba, who opposed philosophy, neither had no problem with the study of Greek medicine (Reponsa part 1, letter 415) nor was he actually against studying the exact sciences.

It is possible that the political changes in Spain helped create the anti-rationalist movement. With the re-conquest of Spain by the Christians, Jews were suffering from the crusades and from the impact of martyrdom in their wake. The Maimonidean synthesis with Greek culture seemed less appealing and a move to mysticism was being felt. After the massive conversion of Jews to Christianity during the months of Spanish rioting against the Jewish communities in 1391, many Jewish scholars regarded the adherence to philosophic doctrine as a threat to the Jewish community; this included Hasdai Crescas (1340–1412 CE) who criticized Aristotelian physics in what was to be one of the first serious attacks on the system (Wolfson 1929).

After the Spanish expulsion, the interest in philosophy dwindled in the Jewish world. With the exception of scholars such as Joseph Solomon Delmedigo (1591–1655) in his book *Sefer Elim*; R. Moses Isserles (1520–1572) of Cracow and R. Abraham de Herrera (1570–1635), who combined philosophy and Kabbalah; R. Menasseh Ben Israel (1604–1657); R. Moses Zacuto (1625–1697), a kabbalist who was in contact with Spinoza; and R. Loew of Prague (1520–1609, known as the Maharal), Kabbalah took over from philosophy as the main intellectual interest.

David Nieto (1654–1728 CE), in his *Second Kuzari*, claimed that the rabbis of the Talmud were never against philosophy (Nieto 1993). In the eighteenth century, scholars like Rabbis Elijah Ben Solomon Zalman (1720–1797, better known as the Vilna Gaon), Jacob Emden, and Jonathan Eibeshitz still held the sciences in great respect. The Vilna Gaon was quoted as saying that for every amount that one lacks knowledge of the general sciences, he lacks one-hundred fold in the study of Torah (Baruch ben Jacob (1780) of Shklov, *Introduction to his translation of Euclid* in Hebrew). The Vilna Gaon even wrote his own treatise on algebra titled, *Ayil Meshulash* (*The Three Rams*), but concurrently he was rather cold towards philosophy (Shuchat 1996).

With the onset of the Jewish emancipation (from the later eighteenth to twentieth century) in Europe and Russia came the rise of the Jewish *haskalah* (*or enlightenment*) movement, which saw its goal to reintroduce secular education to the traditional Jewish masses. In Western Europe, the father of the Jewish *haskalah* movement was Moses Mendelssohn (1729–1786), a traditional and observant Jew well versed and acculturated in German intellectual society. Mendelssohn set out to portray Judaism as a religion of reason in his work *Jerusalem*, using religion and philosophical reasoning hand in hand as Maimonides did before him. The first period of the haskalah (in the late eighteenth century and the beginning of the nineteenth century) saw many religious Jews, especially in Eastern Europe, even rabbis, embracing the message of secular studies alongside Torah studies; however, with the secularization of the Russian and Eastern European haskalah movement, rabbinic leaders disassociated themselves with it and even became antagonistic to it.

Since then, ultra-Orthodox[7] Jewish thinkers tended to disassociate themselves from the study of secular knowledge, especially philosophy and the humanities, even if they had no overall opposition to the exact sciences. An example of such was the voluntary closing of the Volozhin Yeshiva (Seminary) in Lithuania after the government forced its students to include secular studies into its syllabus in the second half of the nineteenth century (Stampfer 2005).

In the Hassidic[8] (ultra-Orthodox) camp as well, there was a feeling of suspicion towards philosophy. However, even Rabbi Nahman Ben Simha of Breslov, the famous anti-rationalist Hassidic leader, who shunned philosophy (Ben Simha 1990) claimed that there was some good in all of the sciences (Likutei Mohran 18).

The revival of secular studies within Orthodoxy in Western Europe is attributed to Rabbi Samson Raphael Hirsch (1808–1888) who coined the term *Torah Im Derech Eretz* (or Torah *with secular knowledge*). Later in the twentieth century Rabbi A. I. Kook (first chief rabbi of prestate Israel) believed that all Torah scholars should have a basic knowledge of general culture and science. This has become the position of the modern-Orthodox stream in Judaism. However, within the ultra-Orthodox world, the exact sciences, i.e., physics, chemistry, and biology (excluding evolutionary biology), are tolerated but the humanities (including philosophy) are viewed with profound distrust.[9]

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[7] In general, Orthodox Judaism is the approach to Judaism that adheres to the rabbinic interpretation and application of the laws and ethics of the Bible as found in the Talmudic literature. In the early nineteenth century, Orthodox Judaism divided into two different camps, the modern Orthodox and ultra-Orthodox which encompass a wide spectrum of beliefs. Nonetheless, Waxman (1998) details three major differences separating modern Orthodoxy and ultra-Orthodoxy. The first involves the ultra-Orthodox stance towards the larger society in general and the larger Jewish community, which is essentially an attitude of isolation, as opposed to the inclusive attitude of the modern Orthodox. The second is in reference to modernity, general scholarship and science, with the ultra-Orthodox being antagonistic and modern Orthodoxy being accommodating, if not always welcoming. Third, there is a basic difference between the two in their attitudes towards Zionism and active involvement in the rebirth and development of Israel, with the ultra-Orthodox being antagonistic and the modern Orthodox welcoming Zionism as a religious value. In this chapter we will use the English term ultra-Orthodox (even with its political connotations) as opposed to the Hebrew term, Haredi, as this is the more common term in English sources.

[8] Hasidism is a branch of ultra-Orthodox Judaism that promotes spirituality and joy through the internalization of Jewish mysticism as the fundamental aspect of the Jewish faith. It was founded in the eighteenth-century Eastern Europe by Rabbi Israel Baal Shem Tov (1698–1760) as a reaction against overly legalistic Judaism identified with Orthodox Jewry in Lithuania (sometimes called Mitnagdim (pl.) or "the opposition"). Today, the ultra-Orthodox community is comprised of both Hassidim and Mitnagdim.

[9] The ultra-Orthodox community saw support for their position in the opposition of the rabbis of the Middle Ages to philosophy. In the argument between the anti-rationalists and the Maimonidean school, for instance, they saw themselves as siding with the anti-rationalists against the Maimonidean embracing of philosophy and secular science.

54.2.4 Cosmology and Cosmogony (In the Modern Period)

54.2.4.1 Cosmology

Despite the seeming open-mindedness towards science in the nineteenth-century Western Europe, there was a greater ambivalence towards science in Eastern Europe indicated by the pain that the parting with the geocentric system of planets had on a few Jewish thinkers. The Vilna Gaon in the late eighteenth century still spoke of a Ptolemaic astronomical system in his commentary to the mystical *Sefer Yetzirah* (*Book of Creation*). Is this due to opposition to the new astronomy or just a lack of awareness? The Gaon studied philosophy and science from Hebrew texts; thus, it is possible that these texts were outdated and therefore could have had antiquated views of science. It is also possible that his ideas were just commentaries on the views in the *Sefer Yetzirah* which was written close to the Ptolemaic period.

Another scholar from Vilna, Rabbi Pinchas Elijah Horowitz (1765–1821 CE), in 1797 CE, published *Sefer Habrit* (*Book of the Covenant*), which acted as a Jewish encyclopedia of science. This volume needs special attention since it was extremely popular in the nineteenth and early twentieth century among Eastern Europe Jewish scholars, as evidenced by its more than 26 editions published between 1897 and 1925 CE in the original Hebrew as well as in Yiddish and Ladino (Robinson 1989).[10] An unusual aspect of this work was its attempt to create a synthesis between science and Kabbalah (Robinson 1989). In the chapters on astronomy Horowitz displays sympathy to the Copernican system but ultimately rejects it in favor of the geocentric position (Rosenbloom 1996).[11]

Rabbi Reuven Landau (as cited by Robinson 1983) of Romania wrote books on trigonometry (*Middah Berurah* or *Clear Measurement*) and astronomy (*Mahalakh ha-Kokavim* or *The Movement of the Planets*). In them, he tried to explain to the reader all the fundamentals of these fields, but he was also careful to integrate an explanation of how the Divine force permeates all of nature (Brown 2008). Despite his knowledge of the new cosmology, he raises objections to Copernicus' proofs and sides with the geocentric universe for spiritual reasons; if the Earth was not the center of creation, possibly humanity was not the center either. Landau, as with Horowitz's *Sefer Habrit* before him, adopts Tycho Brahe's system in which the sun and the moon revolve around the Earth but the other planets revolve around the sun. However, it should be mentioned that in the second edition of this book in 1818 CE, the publisher writes that it is possible for a believing Jew to adopt the Copernican view if he so chooses (Brown 2008).

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[10] Solomon Schechter, the noted scholar of the Cairo Genizah in the early twentieth century, admits that in his youth in a village in Romania, he heard of America through Sefer Habrit (Robinson 1989).

[11] Nussbaum (2002, 2006) shows that in recent years, there has been a revival of geocentrism among some in the Orthodox community including rabbis and scientists; it is unknown how widespread this phenomenon is.

In Bialystok, Hayyim Selig Slonimski (1810–1904 CE) was a talmudist, a mathematician, and a popularizer of science for traditional Jews. Coming from the same mind-set of the Vilna Gaon and *Sefer Habrit* that secular knowledge is needed for the proper comprehension of Torah, he published his first volume on mathematics titled, *Mosdei Hokhma* (*Foundations of Wisdom*) in 1834 with rabbinic approbations (Robinson 1983). In 1838, he published a book on astronomy entitled *Toldot Ha-shamayim* (*The Heavenly Hosts*). He was one of the first to explain that the six days of creation are really six eons and therefore came closer to the ideas of the geology of the time than those relying on Biblically based calculations for the Earth's origins (Robinson 1983). In sum, Slominski looked for synthesis between science and rabbinic literature.

In Western Europe, however, Jewish thinkers seem to have been quicker to accept this new worldview. Raphael Halevi of Hanover (1685–1779 CE) a mathematician and philosopher, who had studied with Leibnitz, published two books in astronomy in 1756 CE. In his *Tekhunat Ha-Shamayim* (*Astronomy of the Heavens*), he openly embraces the Copernican system. It is of interest that Rabbi Landau read this work and quoted from it, without adopting this position (Brown 2008). Similarly, Joseph Ginsburg in his *Ittim La-Bina* (*Wisdom of our Days*) explained that one could accept the Copernican model and remain a faithful Jew. Dov Ber Rukenstein in his two-part series on astronomy entitled *Mesilot Ha-Meorot* (*Pathways of the Heavenly Bodies*) (as cited in Robinson 1983) talked of Copernicus' model as being accepted by all scientists of his day. Therefore, writing in the late nineteenth century, Rabbi Samson Raphael Hirsch could say:

> What Judaism does consider vitally important is the acceptance of the premise that all the hosts of heaven move only in accordance with the laws of the one, sole God. But whether we view these laws from the Ptolemaic or Copernican vantage point is a matter of total indifference to the purely moral objectives of Judaism. Judaism never made a credo of these or similar notions (Hirsch 1992, p. 263).

54.2.4.2 Cosmogony (Including Evolution)

In classical Jewish philosophy, Aristotelian physics and cosmology were seen as a challenge, rather than as an overt threat; thus, although being diametrically opposed to the book of Genesis, great effort was invested in order to reach a synthesis between the Aristotelian theory of the eternity of the universe and the Biblical creation narrative. In the twelfth century, Maimonides in his *Guide for the Perplexed* took great pains to explain how one can explain creation with the same Aristotelian hypothesis but with some alterations.

In the nineteenth century, rabbinic thinkers dealing with the new theories of cosmogony and particularly evolution acted in a similar same way. Orthodox Rabbi Israel Lipschutz of Danzig was a learned legalist who had a great interest in the science. Writing in the 1800s, before Darwin's *On The Origin of Species* was published, Lipschutz was familiar with the "evolutionary" theories of Lamarck. Rather than seeing the new theories as a threat to Biblical belief, he sees the idea of an ice age and the regeneration of life as a proof for the Jewish belief in the eventual resurrection of the dead. No criticism of the theory can be found in his writings, just a great enthusiasm that science is now proving the age old Kabbalistic theory that there were earlier worlds than ours (Shuchat 2005).

In the post-Darwinian world of the nineteenth century, there was still no major change. Jewish thinkers like Rabbis Elijah Benamozegh of Italy and Samson Raphael Hirsch of Germany, writing at the same time that the Church and the scientists of Europe were battling each other verbally, did not see evolution as a major threat to Jewish belief. For example, Rabbi Hirsch writes:

> Judaism is not frightened even by the hundred of thousands and millions of years which the geological theory of the earth's development bandies about so freely. Judaism would have nothing to fear from that theory even if it were based on something more than mere hypothesis, on the still unproven presumption that the forces we see at work in our world today are the same as those that were in existence, with the same degree of potency, when the world was first created. Our rabbis, the Sages of Judaism, discuss [Bereshit Rabbah 9, 2 and Mishna Hagigah 16a] the possibility that earlier worlds were brought into existence and subsequently destroyed by the Creator before He made our own earth in its present form and order. However, the rabbis never made the acceptance of this and similar possibilities an article of faith binding on all Jews. They were willing to live with any theory that did not reject the basic truth that every beginning is from God (Hirsch 1992, p. 265).

Rabbi Elijah Benamozegh (1862) saw the new scientific discoveries as proving the Midrashic and Kabbalistic notion of earlier worlds which God created before our own:

> In conclusion, this belief in earlier worlds is an ancient one in our nation and it stands as a proof for the divine nature of the Torah, which natural science now confirms. . . . And I finish [this discussion] with the dear words of the scholar in the Kuzari [1, 40] who said: 'If a believer in Torah had to admit to the existence of primordial matter of earlier worlds that predated us, this would not blemish our faith' (Benamozegh 1862).

In addition, Benamozegh saw the new theories of evolution as a proof of human potential and ultimately of the resurrection:

> I believe, as science teaches, that animal forms appeared on the earth and evolved into more perfect beings, either as Cuvier said, by revolutions and cataclysms, or by slow evolutionary processes, like the opinion of the modernist Lyell, or Darwin and others. More and more perfect species have developed, one after the other, over the course of millions of years on the face of the earth. The most perfect form is Man. But will nature stop here? This would indeed be strange. Present humankind, as Renan [French expert of Middle East ancient languages and civilizations] says, will evolve into another, more perfect human being. But Renan and the others stop here. They do not say that the order that reigns in the physical world has to reign in the moral one as well, and that there is no reason to believe that the 'I' that force which created the actual human, does not have to create the future human as well. They do not say that the 14 monads, the atoms, which are minuscule forces, are indestructible (as science teaches) for it is inevitable to believe that they will compose the future Man on a regenerated earth. All this is stated by Judaism, and is called the Resurrection (Benamozegh 1877, pp. 276–277).

Similarly, Rabbi A. I. Kook's writing in the early twentieth century also displayed an optimistic view of evolution claiming that it is closer to the Kabbalistic notion of creation than the philosophical idea of creation ex nihilo.[12] Despite this enthusiasm in his more philosophical writings, in his public letters, Rabbi Kook writes more cautiously. After explaining to a correspondent why the new theories of evolution do not contradict the Torah, he writes:

> We do not have to accept theories as certainties, no matter how widely accepted, for they are like blossoms that fade. Very soon science will be developed further and all of today's new theories will be derided and scorned and the well-respected wisdom of our day will seem small-minded Feldman (1986, p. 6).

Continuing this trend, Rabbi Isaac Halevi Herzog (the first chief rabbi of Israel), writing in the mid-twentieth century, displayed the discomfort that many later rabbinic figures were to have with the theory of evolution. This discomfort was caused not just by the challenge which this theory posed to Biblical exegesis but by the fact that it was considered to be one of the paradigms of modern secular scientific thought, which many of these rabbinic figures felt was in opposition to all organized religion (Robinson 2006).

Some rabbis of the second half of the twentieth century began, like their Christian contemporaries, to see the theory of evolution as a threat. As Orthodox Jews entered the arena of the sciences, many of them entered the battle against evolution, arguing from a scientific standpoint, rather than a Biblical or Talmudic point of view, and looked to those who opposed evolution as their comrades in arms (Cherry 2006). Rabbi Herzog's attempt to look for ways to harmonize the simple meaning of Genesis 1 with evolution without the multitude of rabbinic commentaries reflects this new attitude:

> How can the Torah chronology be scientifically defended, in view of the aeons which science postulates for the existence of man upon this earth? There is, of course, the well known Midrash, 'boneh olamotu-maharivan' [he built his worlds from annihilation] [Midrash Genesis Rabbah 3, 7; Ecclesiastes Rabbah 3:11], but this can only help if we assume that "maharivan" does not mean annihilation, so that we can assume that fossils of man asserted by science to be so many hundreds of thousands of years old are relics of a previous earth. Yet anthropology seems to assert upon internal evidence that the present man is already hundreds of thousands of years old! […] Of course, strictly literal interpretation of the Pentateuchal text is out of the question. But super literary interpretation should be resorted to only when reason absolutely rules the literary sense being utterly impossible… (as cited in Shuchat 2008–2009, p. 155).

Rabbinic scholars are not detached from the world around them. During periods of social turmoil, when the thinkers of the age begin to doubt the validity of the scientific order of the day, Jewish thinkers do so as well. The events of the Second World War proved both the supreme power of scientific technology as well as the threatening implications of the misuse of that power. The subconscious social impact of the atom bomb attacks on Japan and a war that used modern technology to claim millions of lives cannot be underestimated. Although faith in science

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[12] The kabbalists had a different take on creationism seeing it more as an act of emanation rather than creation ex nihilo. They also differed on the question of the time that it took to create the universe (Shuchat 2009).

remained unscathed for the first decade and a half after the war, and the scientific community emerged from the war with enhanced prestige, these events planted the seed for the disillusionment with science, in general, and more specifically evolution that put it on the defensive in the 1960s and 1970s (Ben-David 1991).

The technological boom of the nineteenth and early twentieth centuries led to a belief in the omnipotence of science, and religious fundamentalist voices against the theory of evolution were stifled, out of respect for science; by the 1970s, however, attacks on science gained legitimacy, and the popular reaction to science was now a mixture of enthusiastic support and profound mistrust (Ben-David 1991).

In the Jewish world, a second element contributed to increased disdain for science. After the destruction of European Jewry, including all major institutions of Jewish learning and culture, some of the Orthodox rabbinic leadership did everything possible to hold on to what remained and held suspect any new way of thinking that might pose some type of threat to religious survival. These feelings of suspicion towards all new ways of thinking became more manifest in the seventies, as society as a whole became critical of science. As a result, the late twentieth century saw the Jewish attitude to science take on different voices. The theory of evolution, in particular, which was seen as one of the paradigms of modern, secular (scientific) thinking, became representative of how various elements in Judaism see religion and science. The syntheses of classical Jewish philosophy were therefore at times forgotten.

Approaches of Reform and Conservative Thinkers Towards Evolution in the Twentieth Century

The historical picture for Judaism in the nineteenth and twentieth centuries becomes even more complex with the rise of non-Orthodox movements in Europe, which eventually made their way to North America in the late nineteenth century. The non-Orthodox rabbis of the early twentieth century were very committed to finding a way to synthesize between science and Judaism, specifically the modern theory of evolution. The theological debates, which arose in light of the Scopes trial in 1925 over the legality of teaching evolution in public schools in Tennessee (Numbers 1998), generated a discussion among leading Reform rabbis in the United States of how to treat this sensitive issue.

The view of Reform rabbis of the 1920s was identical to their predecessors, Rabbis Kaufmann Kohler and Emil Hirsch of the late nineteenth century, in their belief that fundamentalists had erred in understanding the first verses of Genesis, literally, and in assuming that evolution denied a creator (Swelitz 2006). They argued that Genesis is not a textbook for science and literal interpretations of it were not acceptable. Reform rabbis went as far as claiming that progressive change and design were an inherent part of evolution and therefore provided a case for God as a creator (Swelitz 2006). In the 1930s, Rabbis Cohon, Brickner, and Felix Levy saw the new physics as supporting the view of intelligent design making the evolution of life possible (Swelitz 2006).

Conservative rabbis in the 1920s and 1930s like Levinthal and Finkelstein took the same position as the Reform on this issue (Swelitz 2006). Rabbi Mordecai Kaplan was somewhat of an anomaly at this point adopting a naturalist approach to God that disregarded the theological arguments leading from evolution to God.

In the postwar era of the 1950s and 1960s, Reform Rabbi Emil Fackenheim, Rabbi Abraham Joshua Heschel of the Jewish Theological Seminary, and theological scholar Will Herberg believed that an excessive reliance on science and reason had distorted the proper understanding of Judaism (Swelitz 2006). No evolutionary argument can explain a personal God. It is necessary to demarcate the boundaries between science and religion, they argued.

By the end of the 1960s, evolution was generally ignored by most among the Conservative and Reform, except in the writings of Reform Rabbi W. Gunther Plaut. This position, separating science from religion, was challenged by Reform Rabbis Levi Olan and Roland Gittelsohn and Conservative Rabbi Robert Gordis, who defended the centrality of reason and science in Jewish theology. Gittelsohn was personally interested in evolutionary biology and advocated what he called "religious naturalism" invoking the new science to aid one in proving the existence of God (Swelitz 2006). Gordis shared Milton Steinberg's belief that religion has to provide a philosophy of life which includes the conclusions of science.

In the 1980s there was a renewed interest in evolution, with the attempt by creationists in the United States to gain equal time in public schools for teaching Biblical creation. However this time, Reform rabbis, like William Leffler and Jack Luxemburg, maintained the need to emphasize the limitations of science in proving or disproving God (Swelitz 2006). This apparent divorce of science from religion in the 1980s was followed by evolution reentering Jewish theology with the renewed interest in Kabbalah. The idea of cosmic evolution was adopted by Reform Rabbi Lawrence Kushner as well as Rabbi Zalman Schachter-Shalomi of the Jewish Revival Movement and Prof. Arthur Green.

Approaches of Ultra and Modern-Orthodox Thinkers Towards Evolution in the Twentieth Century

Turning to the postwar Orthodox world of North America, we see that the situation was different. It was mentioned previously that Rabbi Herzog was hesitant in utilizing the rabbinic notion of earlier worlds and preferred to see if there were scientists who held other views. The second half of the twentieth century saw Orthodox responses to evolution, which were much different than those of the late nineteenth and early twentieth centuries. The ultra-Orthodox saw evolution as representing a secular alternative to the religious weltanschauung and therefore saw it as stepping over its legitimate boundaries. Rabbi Moses Feinstein claimed that

> Textbooks of secular studies that contain matters of heresy with respect to the creation of the world… are forbidden to be taught…If it is not possible to obtain other books, it is necessary to tear out those pages from the textbook (Feinstein 1982).

More modern-Orthodox thinkers looked for inroads to recreate the syntheses of earlier days. Like his predecessor Rabbi Herzog, Rabbi Aaron Lichtenstein wrote in the late twentieth century:

> Confronted by evident contradiction [between Torah and science] one would… initially strive to ascertain whether it is apparent or real… whether indeed the methodology of madda [science] does inevitable lead to a given conclusion, and … whether… Torah can be interpreted… so as to avert a collision (Robinson 2006, p. 78).

An interesting phenomenon that developed in the second half of the twentieth century, with the entry of Orthodox Jews into Western universities, was the place of the Orthodox Jewish scientist. In 1948, some of these scientists founded a group they called the *Association of Orthodox Jewish Scientists* (AOJS). One of its aims was to resolve "apparent challenges of scientific theory to Orthodox Judaism" (Robinson 2006, p. 79), and evolution, specifically, was an important issue that they needed to deal with.

In the late twentieth century, three Orthodox Jewish physicists can be seen as representing three different approaches to evolution: Prof. Hermann Branover, Prof. Nathan Aviezer, and Prof. Gerald Schroeder. The American-trained Prof. Aviezer (1990) of Bar-Ilan University in Israel, in his work *In the Beginning*, took a nonliteral attitude to the 6 days of creation, seeing them as epochs rather than days of 24 h, but then continues to read into the literal text a novel interpretation in which he claims that the main elements of the Biblical story harmonize with all the main elements of modern scientific cosmogony (Cherry 2006). Aviezer also takes a non-chronological reading of the creation story in which he sees the 6 days of creation as representing two stages: days 1–4 which represent the formation of the structure of the universe and days 5–6 which represent the inhabitants of the universe which begin while the universe is being formed.

The second approach is from another American-trained physicist from Israel, Gerald Schroeder. Schroeder (1998) accepts, as does Aviezer (2002), the evolutionary timetable; however, in a novel literary hermeneutic, he claims that the 6 days of creation were 6 days of 24 h, but claims that according to Einstein's theory of relativity and time dilation, from the perspective of the forward rushing cosmos ("God's perspective"), 6 days is equivalent to 15 billion years looking backwards.

A third perspective is that of Russian-educated Prof. Hermann Branover of Israel. Associating himself with the ultra-Orthodox Hassidic community of Lubavitch, he holds a literalist view of the creation story. He uses alternative scientific views to argue against scientific evolution.

Ultra-orthodox groups such as the Israeli outreach organization "Arachim" feel more comfortable with these more aggressive fundamentalist anti-evolution positions. The open attacks of these fundamentalists against scientific thinking have gone so far as to find among them those who now are even questioning again Copernican heliocentricity in the twenty-first century. Moderate elements in the ultra-Orthodox world, such as the Aish Hatorah outreach organization, see Schroeder's position as saving both creationism and science, whereas modern-Orthodox Jews feel comfortable with Aviezer's ideas or just accept a nonliteral interpretation of the creation story (Sacks 2011).

Evolution aside, mainstream Orthodox Jewish rabbinic thinkers tend to adopt a generally positive attitude to science. This view of the legitimacy of science to overcome the Biblical curse of the ground mentioned earlier or to heal the sick is the age-old Jewish view which sees the idea of scientific progress as a way of mending the world when used for the good.

54.3 Historical Summary

This brief historical overview shows a somewhat complicated relationship between Judaism and science, but certain tendencies can be deduced from it. As we have seen, from earliest times, technology was seen positively as something that can help mankind overcome the difficulties of life. The Talmud praises the study of astronomy and sees biology and medicine as legitimate fields of study. The Jewish rationalists of the middle ages, especially in Spain, were particularly open to general studies and well versed in the sciences, medicine, and philosophy of their day.

The debate over philosophy in the post-Maimonidean era seems to have been more of an attack against lax observance, as well as the non-Orthodox ideas of the rationalists, than a ban on science per se. Philosophy was often seen as the culprit which brought in foreign ideas to Judaism. This same style of controversy can be seen in the middle to late nineteenth century Eastern Europe between the secular exponents of the Haskalah (or enlightenment) and their rabbinic counterparts.

The late nineteenth century saw the rise of Darwinian evolution and its entrance into Jewish thinking. Early thinkers until the First World War had an open and even accepting attitude, but in the post Second World War period, suspicion arose and the fear of foreign elements challenging Jewish faith renewed the debate over the relationship of science and Judaism. Most modern orthodox, as well as well as almost all Conservative and Reform thinkers, showed an attitude of acceptance; in contrast, the postwar ultra-Orthodox camp, suspicious of most modern concepts, showed antagonism to these ideas, even if they did not oppose the study of the sciences for the need of a livelihood or to practice medicine. Jewish educators abroad and in the educational system of the State of Israel struggle to this day to accommodate these different philosophical approaches, as we will see in the next sections of this chapter.

54.4 Philosophical Approaches Towards the Interaction Between Science and Judaism

Our brief historical survey confirms what Efron (2007) previously noted about the attitudes of Jewish thinkers towards science, in that historically it was "never subject to consensus." Certainly, we have seen that there were specific periods and regions where (rabbinical) authorities were worried about how secular science might affect Jewish piety and so strongly opposed contact with secular learning, including science, or specific scientific disciplines. At the same time, Judaism has often looked positively upon science, and its precursor, the study of nature and astronomy in antiquity, not just in its applied form where it benefits man's ability to derive a living or protect one's health but also in order to gain a better understanding of the natural world.

Moreover, Efron (2007) suggests that Judaism has avoided many of the science-religion clashes that have occurred among the Christians. In part, this was due to the fact that Jews never developed institutions with the coercive power to declare an idea or a book to be an anathema.[13] More importantly, in his view, the long exegetical tradition within Judaism of reading and interpreting texts meant that Jews by their nature did not sanctify the ideal of consensus. In fact, Jewish exegetes actively sought to multiply interpretations to arrive at deeper understandings of a text. Indeed, we can see this tradition of multiple interpretations operating in our brief historical review in the previous section of this chapter.

Thus, even if there might have been a mainstream trend during any period of Jewish history concerning how Judaism saw science, or any of its disciplines, from a practical viewpoint, rather than looking for consensus, it is better to discuss a spectrum of philosophical approaches that were developed to classify the (multiple) positions of Judaism towards science. In this section, we will discuss these approaches in order to create a set of definitions that can be applied to our discussion about Judaism and its interaction with science education.

Much of the work dealing with the philosophical interaction between religion and science has focused on Christian perspectives. The four most comprehensive works on this interaction include the books of Barbour (1997), Brooke (1998), Haught (1995), and McGrath (1999).

Among sources dealing with Judaism's interaction with science, there are two comprehensive works: Lamm's (2010) *Torah Umadda* and Rosenberg's (1988) *Science and Religion in the New Jewish Philosophy* (published in Hebrew). Both works are important but emphasize different approaches. Lamm's (2010) work is somewhat broader in that it deals with how Jewish thought has dealt with worldly knowledge, in general, rather than just science, which is Rosenberg's focus. From a practical perspective, Rosenberg's (1988) work has been used in a number of science education studies to classify the positions held by religiously Jewish teachers (Dodick et al. 2010) and students (Allouch 2010) in Israeli schools, and so we will examine his approaches here, as a precursor to our discussion of science education; nonetheless, whenever possible, we will integrate Lamm's (2010) discussion.

In structure, Rosenberg's (1988) approaches are somewhat similar to those mentioned in Barbour (1997) albeit the number of categories he developed was larger. Moreover, both Rosenberg (1988) and Lamm (2010) develop a set of approaches or models based on Jewish thinkers and their interpretation of classical

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[13] One of the most famous historical examples of the use of coercive power in the Christian world was the Church's imprisonment of Galileo as a heretic in 1613 for his support of the heliocentric theory. Bronowski (1973, p. 218) argues that "the effect of the trial and the imprisonment was to put a total stop to the scientific tradition in the Mediterranean."

Jewish texts (such as the Talmud and Midrash) which contrasts with Barbour's approach in which he delineates a set of historical-based Christian attitudes towards science. Thus, Lamm (2010) and Rosenberg (1988) provide us with greater insight than Barbour (1997) when we examined science education and its interaction with Judaism. In his book, Rosenberg (1988) talks about four main approaches.

54.4.1 Limiting Approach

This approach opposes any attempt at integrating secular knowledge with Jewish thought. From this point of view, such a mixture creates the chance that heresy may infect the student of Torah; therefore, from a practical perspective, there was no room in the curriculum of a Torah student for such lesser knowledge (Lamm 2010). When faced with a scientific approach to problematic issues such as creation, those adopting this approach reject the scientific approach, as it challenges the primacy of the Bible's literal meaning. An example of this approach can be found in the writings of the late Rabbi Menachem Schneerson the former leader of the Lubavitch Hassidic movement in his commentary concerning geologic time and evolution:

> In view of the unknown conditions which existed in prehistoric times (atmospheric pressures, radioactivity) conditions which could have caused reactions of an entirely different nature and tempo from those known under present-day processes of nature, one cannot exclude the possibility that dinosaurs existed 5,722 years ago, and became fossilized under terrific natural cataclysms in the course of a few years rather than millions of years (Schneerson 1972).

In philosophical terms, Rabbi Schneerson (1972) was rejecting the principle of uniformity which states that the laws of nature remain unvarying throughout time. This approach to secular learning, in general, and science specifically is most common among the ultra-Orthodox. Such explanations also *seem* to match most closely with a Christian fundamentalist view of religion and its relationship to science, most notably those issues connected to creation and evolution.[14]

54.4.2 Explanatory Approach

In this approach, Biblical texts are not understood literally, but rather are explained so that religion and science can be brought closer together. Contradictions are

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[14] Regarding evolution, Robinson (2006) argues that care should be taken in blindly comparing ultra-Orthodox attitudes to fundamentalist Christians too closely. The ultra-Orthodox are united in their opposition to Christian creationism as it is based on the King James Bible and not on traditional Jewish texts, which incorporate the cumulative perspectives obtained from (a large number of) traditional Torah commentaries and interpretations. In fact, Robinson (2006) could only find one source written from an ultra-Orthodox perspective whose author identifies as a creationist. Thus, at least in philosophy, if not deed, the ultra-Orthodox do differ from fundamentalist Christians.

viewed as a misunderstanding of the Bible and simply require proper interpretation. For example, with regard to the Earth's age, some Jewish Biblical commentators explain that the days of creation went far beyond a 24-h period of time, or as Rabbi Abbahu states in the Midrash that "God created [many] worlds and destroyed them until he created this one" (Rabba Bereshit, 3, Sect. 7). Thus, according to this interpretation, there were cycles of destruction and creation culminating in this world, such that the age of this world far exceeds the 6-day period of creation.

Among the most important exponents of the explanatory approach was Maimonides. More than that, his attitude to secular studies, in general, was not just that it was permissible but that there was an "obligation to pursue them as an act of mitzvah" (i.e., religious command) (Lamm 2010, p. 67).

54.4.3 Parallel Approach

This approach sees contradictions between science and religion as being derived from not clearly separating between the domains, as the former deals with rational explanations of nature, while the latter focuses on religious belief which illuminates human purpose, meanings, and values. Each domain has value for human experience, but they should not be integrated. Scientist and philosopher Yeshayahu Leibowitz is a noted exponent of this approach:

> There is no mutual dependency between scientific knowledge and decisions about [religious] values. What can the immense achievement of science contribute to these decisions on values? Science cannot contribute anything because concerning the problem addressed by these decisions, such as to be a believer, not only does science have nothing to contribute, but these questions cannot even be posed because these concepts do not appear in the lexicon of science (Leibowitz 1985, p. 35).

Historically, one of the more important exponents of the parallel approach in the Jewish world of education is Rabbi Samson Raphael Hirsch's Torah Im Derech Eretz ("Torah with secular knowledge") (Lamm 2010) whom we discussed previously. This approach also represents, as we have seen, the position of Reform Rabbi Emil Fackenheim, Rabbi Abraham Joshua Heschel of the Jewish Theological Seminary, and the theological scholar Will Herberg. Philosophically, the parallel approach is also equivalent to scientist Stephen J. Gould's (1997, 1998, 1999) principle of "respectful noninterference" between the worlds of science and religion or *NOMA* (Nonoverlapping Magisteria).

54.4.4 Complementary Approach

This approach suggests that science complements religion, creating a synthesis of the sacred and secular. Supporters of this approach see a strong (though not necessarily literal) fit between scientific discoveries and what is described in the Bible (Lamm 2010). This approach is personified by Rabbi A. I. Kook who viewed the theory of evolution as a model for spiritual growth; thus, he did not see it posing a threat to religion:

> The theory of evolution that is presently gaining acceptance in the world has a greater affinity with the secret teachings of the Kabbalah better than all other philosophies. Evolution which proceeds on a course of improvement offers us the basis for optimism in the world. How can we despair when we realize that everything evolves and immediately improves? In probing the inner meaning of evolution toward an improved state, we find here an explanation of the divine concepts with absolute clarity. Evolution sheds a light on all the ways of God (Kook 1938, p. 555).

54.4.5 Conflict Approach

This approach was not found in Rosenberg (1988), but it emerged as a consequence of interviews that were held by Dodick et al. (2010) with religiously observant Jewish teachers (in the Israeli high school system) and scientists (in the Israeli university system); it was therefore added to the taxonomy used by Dodick et al. (2010) to classify the philosophical approaches of religiously oriented, Jewish teachers and scientists. Conflict emphasizes the understanding that there sometimes exists a contradiction between science and religion because of the overlap between the two domains such as occurs with evolution. Such conflict largely arises because of the open, unanswerable questions that occur due to this overlap. Nonetheless, although some are affected by this conflict, they are willing to live with the situation and do not reject science as is the case with the limiting approach.

54.5 Judaism and Its Interaction with Science Education

In discussing Judaism and its interaction with science education, it should be understood that prior to the emancipation period in Europe, Jewish contact with general secular learning and science learning, specifically, was largely limited to those rabbis who approved of and conducted such learning (Efron 2007). Thus, it is impossible to talk of the interaction between Judaism and science education on a large scale before that time period. Even post-emancipation, there is no published research dealing with science education until we enter the twentieth century. Therefore, we will confine our discussion to recent times because all of the education research that has been conducted on this topic has been done in the last 20 years or so.

Unfortunately, there are only a small number of studies dealing with the interaction between Judaism and science education, especially when compared to the larger number of studies from a Christian perspective. This is due to a number of interrelated factors. Most science education studies dealing with the interaction between science and religion emanate from Western countries, where the dominant religious background (measured by population) is Christian. Therefore, by default, such studies are strongly flavored by a Christian perspective because the majority of school-age students come from a Christian background.

Hence, if we are to understand how Jewish attitudes towards science influence science education, we need to discuss the situation where Jews represent the majority and thus influence the school system. If we are talking geographically, we must focus on Israel, the only country with a Jewish majority. If we are talking systemically, we can also include the extensive private Jewish school systems that have developed in Western countries, most notably in the United States, which contains the world's second-largest Jewish population after Israel (DellaPergola 2010).[15]

Historically, for those groups of Jews who were not opposed to the integration of secular knowledge into the Jewish domain, the scientific issues that are most challenging to Judaism emanate from subjects touching upon Biblical creation including cosmology, geologic time, and most notably evolution. Not coincidentally, these issues have also had the greatest impact on the interaction between Judaism and science education, and it will be a discussion of these conflicts that will dominate this chapter.

However, before analyzing this conflict, we must discuss Jewish school systems, both within and without Israel, because their structure affects how controversy is dealt with. Indeed, school systems that serve the Jewish public are guided by a specific religious philosophy and in turn this philosophy guides the school system's interaction with secular subjects such as science, so it is important that we discuss their basic structures.

In Israel, the school system is divided between Hebrew and Arabic speakers. The two largest divisions among the Hebrew-speaking system are the Secular State and National Religious systems, respectively (Dodick et al. 2010). The Secular State system teaches a population of primarily secular and traditional students with many of its teachers coming from secular backgrounds. Its matriculation system is designed so that students have the possibility for continuing to higher academic studies. The only component of "religion" in this system is that the Bible is one of the core subjects (and is taught as part of the cultural background of Israel, and not from a religious perspective).

In contrast, the National Religious school system's philosophy is to integrate secular and (Orthodox-based) religious studies, making it possible for its students to pursue both secular studies at a university and religious studies at a Jewish seminary.[16] Many of the teachers are religious in orientation and have a professional background from a university, college, or seminary, depending on the subjects they teach.

A third system of schools in Israel, termed independent, focuses exclusively on the ultra-Orthodox population. For male students, the focus is on religious studies with little to no secular studies, including science learning; the ultimate goal is to prepare them for higher religious studies in a *Kollel*.[17] There is more flexibility in

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[15] Of the approximately 13.5 million Jews in the world in 2010, Israel's Jewish population accounted for 42.5 %, and the United States' Jewish population accounted for 40 % of the total (DellaPergola 2010).

[16] Philosophically, Israeli-based National Religious schools are most similar to modern-Orthodox day schools outside of Israel.

[17] A Kollel is a Yeshiva learning program for married men.

the education of the female population who study secular subjects, including some subjects in science, out of a practical need to secure their families' financial futures. However, studies in the female ultra-Orthodox system do not usually lead to higher academic learning.

Outside Israel, concerns about inculcating youth in the practices and religious literature of Judaism spurred on the development of private "day" schools as well as afternoon schools, among the various denominations of Judaism in many Western countries. Day schools offer a "dual" curriculum, offering a secular program including science and math, as well as course offerings in traditional Jewish subjects such as the Bible, Hebrew, and Jewish history. With the exception of ultra-Orthodox schools, secular subjects share equal time with religious subjects including science (as part of a longer school day). This means that the majority of graduates from (k-12) Jewish-based schools are well displaced to tackle higher education, if they so desire. Afternoon schools offer various Jewish subjects and are attended by students who attend secular schools during the day.

In the case of the ultra-Orthodox within Israel (as well as sometimes outside of it) secular learning is (largely) omitted for its male population because religious subjects take priority; all the more so, scientific issues of creation are not taught because they challenge the belief in God's creation. In simple terms, they have strongly adopted a limiting philosophical approach. In the exact opposite way, scientific issues of creation pose much less difficulty to the liberal branches of Judaism, including the Conservative and Reform movements[18]; thus, they are taught as a usual part of the science curriculum.

However, the situation is different within modern-Orthodox schools. Although most are committed to a *Torah Umadda* (*Torah and Science*) philosophy, which believes in the integration of religion and secular learning, creation issues can test that resolve, creating conflict, so this group will be a prominent feature of our discussion.[19]

We begin this discussion by examining both the philosophical approaches of the schools and the teachers that work within these schools. We start here, because the roots of students' approaches to the conflict between science and religion are

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[18] As we have seen, Swelitz (2006) extensively explored the historical responses of Conservative and Reform rabbis towards evolution. Using Rosenberg's (1988) system, their responses can be classified as falling within the parallel, explanatory, and complementary approaches. They do not adopt a limiting approach, in contrast to some among the Orthodox. Looking at the Conservative movement today, although they appear to have no official position, many of their Rabbis have adopted the idea of theistic evolution. Rabbi David Fine, who has authorized official responsa for the Conservative movement's committee on *Jewish Law and Standards*, expressed this idea as the following: "Did God create the world, or not? Is it God's handiwork? Many of the people who accept evolution, even many scientists, believe in what is called 'theistic evolution,' that is, that behind the billions of years of cosmic and biological evolution, there is room for belief in a creator, God, who set everything into motion, and who stands outside the universe as the cause and reason for life" (http://www.jewishvirtuallibrary.org/jsource/Judaism/jewsevolution.html).

[19] It will also be seen that almost all of the empirical studies that examine the relationship between Judaism and science education focus on the modern Orthodox, so this is another reason for this focus.

strongly shaped by how they understand science, its nature, and its relationship to religion and it is the schools and their teachers that most strongly shape this understanding. It might also be added that school choice both reflects and is influenced by informal sources – parents and religious authority.

Outside of Israel, Selya (2006) has completed the only major study concerning modern-Orthodox day high schools and their perspectives towards evolution. Surveying 12 such schools in the United States and Canada, she discovered four approaches for teaching evolution (that largely match the philosophical approaches of Rosenberg 1988). These approaches include curricula where evolution is taught in class without a religious discussion, whatsoever (parallel approach). In other schools, teachers teach evolution with the aid of a religious teacher or rabbi who interprets the creation story either in a nonliteral way (explanatory) or from an intelligent design perspective (limiting/complementary). A third perspective is assigning students' readings on evolution without discussing them in the class (sometimes because it was part of the mandated final year examinations) (parallel approach). Finally, evolution was not taught at all (limiting approach).

There were no instances of substituting a creation-science curriculum to replace the standard biology texts or of school administrators removing the chapter from the science textbooks as reported by Wolowesky (1997) and Landa (1991); the latter, as we have seen, was recommended by Rabbi Feinstein (1982), one of the most important ultra-Orthodox rabbinic decisors of Jewish Law in the twentieth century.

Selya (2006) showed that ten of the schools surveyed taught evolution in the classroom and that eight of them suggested that this scientific theory was religiously compatible. Not surprisingly, schools that separated the sexes, a sign that a school is more religiously oriented, either did not teach evolutionary theory or criticized it as being incompatible with religion.

As part of this research, Selya (2006) also interviewed teachers and administrators at five of the schools, all of which were coeducational, with strong college preparatory programs, and which both teach evolution and stress its compatibility with religion. All of these schools share certain philosophical and/or historical roots, including a commitment to the Torah Umadda philosophy. Three of the schools were founded by prominent rabbinic figures, one of whom was Rabbi Joseph Soloveitchik who is considered to be the unofficial leader of modern Orthodoxy during much of the twentieth century.

In sum, Selya's (2006) survey seems to show that evolution is being taught in some form in the majority of modern-Orthodox day schools. However, caution should be applied to her small-scale survey, as in the United States (alone), there are 86 schools, accounting for more than 27,000 students, classified as being modern Orthodox (Schick 2009).

Although further studies, like Selya (2006), are needed, Schick's (2009) demographic studies of Jewish day schools in the United States indirectly may point to a trend of increased resistance to science subjects that are considered to be controversial, such as evolution, among Orthodox Jews. Although the numbers of students increased in modern-Orthodox schools from 1998 to 2009, the number of students that were learning in ultra-Orthodox schools increased at a much faster rate. This is due to the much higher birth rate of the ultra-Orthodox which is more than twice that of the modern Orthodox.[20] And if the school is based on an ultra-Orthodox philosophy, it is more than probable that evolution was not part of their science curriculum.

Moreover, among the modern Orthodox, there are factors that indicate some of its adherents are moving towards ultra-Orthodoxy, a process Waxman (1998) labeled "Haredization" (based on the Hebrew term for ultra-Orthodox). This phenomenon has been documented over a 20-year period by a collection of historians and social scientists.[21] A small (educational) indicator of this shift is the fact that *Torah Umesorah*, the National Society of Hebrew Day Schools, an umbrella organization that provides educational materials to Orthodox schools is increasingly distancing itself from coeducational institutions, which is one indication of increased religious practice.

There are many reasons for this shift, but the most important factor for science education is the increasing number of ultra-Orthodox Jewish teachers who are now teaching in modern-Orthodox schools (Heilman 2005; Helmreich and Shinnar 1998). As most in the modern-Orthodox world have avoided teaching, due to its lower remuneration and lack of prestige in comparison to many other professions, the modern-Orthodox school system has turned to ultra-Orthodox teachers (especially for its Jewish studies departments), which in turn affects the philosophy of the schools and their students (Heilman 2005; Helmreich and Shinnar 1998).[22]

Inside Israel, research has focused on teachers within the National Religious system, rather than the school as the unit of analysis. Such research has importance because teachers, like the schools they teach in, are one of the most critical factors influencing the balance between Judaism and science education. We say this because, as Rutledge and Mitchell (2002) have noted, teachers' attitudes and views about a subject directly influence their instructional decisions on how to teach a subject. Their research shows that teachers' background in the philosophy of science and knowledge of evolution influences their acceptance of and willingness to teach evolution. One would assume that a similar relationship exists for scientific subjects that are considered to be challenging to Judaism.

In a similar vein, Dodick et al. (2010) surveyed teachers in the National Religious school system to understand their philosophical approaches towards the interaction between Judaism and science. In total, 56 teachers were extensively surveyed using a Likert-type questionnaire developed for this research, which surveyed the

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[20] As Schick (2009, p. 12) notes, "In the 1998 census, I reported that there were 3.26 children in the families of Modern Orthodox eighth graders as compared to 6.57 and 7.92 children respectively in yeshiva-world and Hassidic families."

[21] Friedman (1991), Heilman (2005), Helmreich and Shinnar (1988), Liebman (1988), Soloveitchik (1994), and Waxman (1998)

[22] Heilman (2005, p. 265), based on a personal communication with Schick, who has completed a series of demographic studies on Jewish day schools in the United States, claims that "nearly two-thirds of today's Judaica teachers in day schools come from the haredi [ultra-Orthodox] world."

teachers' approaches to the nature of science in general, geologic time, cosmology, and evolution. Eleven of the teachers were also randomly selected for interviews.

Additionally, 15 (Orthodox) scientists from the major branches of science were surveyed with the same instruments to both contrast their views with the teachers, as well as to better understand their coping strategies when confronted by scientific topics that challenge their beliefs. In the cases of both teachers and scientists, their philosophical approaches were classified according to Rosenberg's (1988) typology.

Results indicated that no single philosophical approach earned an overwhelming support from the teachers or scientists. Instead, the teachers and scientists related separately to each source of possible conflict, such as evolution, in accordance with the philosophical approach that appears to be the most fruitful for resolving a specific conflict.

The teachers did differ from the scientists in their stronger preference towards philosophical approaches which help them better integrate the domains of science and religion. Thus, the teachers favored the explanatory and complementary approaches, whereas the scientists most preferred the explanatory and parallel approaches. Possibly, the teachers favor an integrative approach because they prefer answers that avoid delivering an open, contradictory message to their students and through them to their parents and school administrations.

With regard to the scientists, tenured in academia as they are, they have the security to research issues that are both open and controversial. This also explains why some scientists adopted a conflict approach (their third most favored approach), as they acknowledge that some problems are open and (currently) unsolvable, while concurrently accepting the inherent contradictions in this situation. Unlike the teachers, however, none of the scientists adopted a limiting approach, as they saw no reason to constrain the science they practiced. This last result is important because it counters critiques (such as Nussbaum 2002) that highlight Orthodox Jewish scientists who are charged as being antiscience towards issues such as evolution. In other words, it supports the idea that there truly is a spectrum among scientists who are also Orthodox in practice.

On specific issues of conflict, geologic time was much less controversial for teachers than either cosmology or evolution. With this issue, the teachers referred directly to religious sources which implied that were either multiple creations of older worlds or that each day of creation was much longer than 24 h. The teachers' flexibility was based on the openness of classic Biblical commentators on this issue. Such commentators provide sanction for interpreting the Bible, but particularly with the age of the Earth, this sanction has greater impact because there is no direct reference within the Bible to the traditional Jewish calculation of the age of the Earth.[23]

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[23] Some Jews believe that the Earth is currently 5,722 years in age (in 2012 CE). In fact, this figure, which has also influenced Christian fundamentalists' understanding of the Earth's chronology, has been calculated based on the interpolation of ages of Biblical personalities mentioned in Genesis starting from Adam's creation on the sixth day of creation (this calculation can be found in the book Seder Olam Rabbah, ascribed to the second century CE Rabbi Yossi ben Halafta). In turn, this calculation leaves the possibility of interpreting the first 6 days of creation before man's appearance as being much longer than six 24-h days (Dodick et al. 2010).

Thus, it becomes easier for teachers, who are familiar with such commentaries, to accept geologic time.

In contrast to the age of the Earth issue, approximately half of the teachers saw some conflict between the theory of evolution and Biblical creation because its random nature contradicts the belief in creation directed by the "hand of God"; moreover, some cited the fact that it also conflicted with their belief in man as the "crown of creation." It should be noted that some scientists also felt such conflicts but they were willing to live with them.

At the university level, inside Israel there is one comprehensive university that integrates "Jewish heritage" and secular studies – Bar Ilan. Its Faculty of Life Sciences provides courses in evolution, as well as integrates this subject within its various course offerings. In the United States there is a strong dichotomy between the approach of Yeshiva University, whose very motto incorporates Torah Umadda and other Orthodox institutions of higher learning. Indeed, university President Richard Joel (2003, p. 3) in *YU Review* claimed that a "moral underpinning" for science at his university was "to marry the wisdom of faith with the need to explore our universe's mysteries."

In the same issue of this magazine, biology Professor Carl Feit noted that he saw no contradiction between Judaism and biology while arguing that the evolutionary ideas could actually be used to serve to strengthen one's faith (Eisenberg 2003). In a conversation with Selya (2006), Feit notes that he includes evolution as part of his course syllabus while adding readings from the philosophy of science, philosophers, and Jewish Biblical commentaries.

In contrast, Touro College, which was founded in 1971 to "enrich the Jewish heritage" and serves a largely ultra-Orthodox student population, takes an unsympathetic view towards evolutionary biology. As a psychology instructor at Touro, Nussbaum (2002) elicited great opposition from his students for his support of teaching evolution. Moreover, the science professors at this institution routinely criticized evolution while teaching creationism.

Schools and teachers set the curricular standards which ultimately affect students; thus, to complete our understanding of the interaction of Judaism and science education, we will be looking at studies dealing with students. Of these studies, those concerned with k-12 students have emanated from Israel.

Ruach and colleagues (1996) performed a comparative survey study with 185 students evenly distributed among National Religious and secular state students in middle (grade 9) and high schools (grades 11 and 12). The middle grade high school cohort had not yet learned evolution in contrast with the high school cohort. After learning evolution the high school students from both school systems substantially increased their knowledge of evolution. However, their attitudes towards this subject were in opposition. The students of the National Religious stream increased their acceptance of creationism, whereas the Secular State students increased their acceptance of evolution.

More recently, Allouch (2010) also examined the attitudes of middle (grade 9) and high school (grade 10) students from the National Religious school system. This sample consisted of 369 students, 79 of them who were studying evolution.

The design of this study relied upon a Likert-type questionnaire (37 statements) that focused on evolution but also included a small number of statements dealing with the nature of science, cosmology, and geologic time.

Similar to the teachers sampled by Dodick et al. (2010), prior to studying the unit, the students were more accepting of a nonliteral reading of the Biblical creation time line, as well as the "Big-Bang" explanation of cosmology, than they were of evolution. Post-program, a similar result occurred. Positive attitudes connected to time and cosmology improved significantly (despite the fact that this was not the focus of their learning), whereas for the most part, their attitudes towards evolution remained at a no agreement level, even after learning the unit.

Again, similar to the teacher sample of Dodick et al. (2010), the students displayed a variety of philosophical approaches towards different issues, although based on Allouch's (2010) results, the students seem to be more conservative (religiously) in their attitudes towards these creation issues than their teachers. Nonetheless, like the student sample of Ruach and colleagues (1996), the students significantly improved their understanding of some of the issues connected to evolution (most notably Natural Selection). In sum, the results from both Ruach and colleagues (1996) and Allouch (2010) parallel the findings of Lawson and Worsnop (1992) with US students who found that a change in knowledge (about evolution) was not necessarily associated with a change in (religious) attitudes.

It must be remembered that in the case of the students in the religious stream they are exposed to far more religious learning than learning about evolution and this would likely affect their attitudes. In fact, Allouch's (2010) study showed that one of the external factors which influenced the students developing a greater acceptance of evolution was the number of curricular hours devoted to this subject. Moreover, for this group of students, part of their school success is measured by how they understand and apply their religious training; in their community, such application is seen as having great value.

It would be expected that difficulties with issues connected to evolution would also affect Orthodox students who attend university. This was addressed by Nussbaum's (2006) survey study among a sample of 176 Orthodox Jewish students at a single public college in New York City. This study provides for some rather disheartening conclusions about the state of science education among Orthodox Jews. The responses received to questionnaire probes dealing with evolution, such as "Evolution correctly explains the origin of life," and geologic time, such as "What is the age of the universe?" indicate that the subjects tended towards creationist or intelligent design perspectives. Moreover, Nussbaum's (2006) data also seems to show that the students that were science majors were even less accepting of mainstream science than those who were not science majors.

However, we should be careful in viewing this study as a summary of the attitudes of all Orthodox university students in the United States because of its methodological problems. The sample consisted of 176 subjects, surveyed at one university, with little demographic data collected concerning the subjects (such as school background). Moreover, the wording of some of the probes is to be questioned. For example, "Evolution correctly explains the origin of life" with a binary answer format would necessarily exclude theistic-evolutionist approaches.[24] Finally, interviews were not held with any of the subjects, which would have more deeply probed their philosophical approaches. Still, given the fact that Jewish Orthodox society is moving towards more ultra-Orthodox views, the results of this study do seem to reflect such societal change.

54.6 Conclusion

In looking at the relationship between Jews and science education in our modern world, we see mostly positive trends. This might be a surprising conclusion in light of what was written in the previous section; however, these trends are supported by historical, sociological, and demographic factors.

Those denominations in Judaism who have difficulties with science learning, most notably the ultra-Orthodox, and some of the modern Orthodox represent a demographic minority; in total, the Orthodox in the United States represent no more than 13 % of the Jewish population (Ament 2005).[25] Thus, over all, it is possible to say that among Jews connected to their Judaism, methods have developed, historically, in order to deal with the conflicts posed by modern science.

Indeed, it is possible to say that Reform and Conservative Jews have few or no problems with modern science education; this is why their role is downplayed in the previous section which discussed science education. There is simply no evidence that what is considered to be a challenge by some in the Orthodox world is considered to be the same in schools belonging to the Conservative and Reform movements. Thus, it would seem that science is taught in their day schools in the same ways as it is taught in the public school systems.

Moreover, it must be remembered that even among those Orthodox Jews that are challenged by scientific findings, it is *not all of science* that is considered to be a challenge, but specific sciences that touch upon issues of Biblical creation. This is the reason why our review of the science education research has not focused on science in general, but specific issues, such as evolution which are considered to be threatening to the religious sensibilities of its followers.[26] In fact, most modern-Orthodox day schools in the United States are known for the high quality of their secular studies including science education.

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[24] Theistic evolution claims that God's method of creation was to design a universe in which various systems would naturally evolve.

[25] Among those of Jewish origin, who see their faith as an integral part of their lives, the Orthodox represent a higher percentage than stated; still the Orthodox do represent a minority when compared to the number of Jews belonging to movements such as the Conservative and Reform.

[26] Simply put, there are no science education studies that have examined Jewish attitudes/approaches towards science as a whole. All of the known studies focus on one or a few specific subjects such as geologic time, cosmology, and especially evolution, which (supposedly) are threats to the Jewish worldview.

It should also be remembered that although there is large demographic growth within the worldwide Orthodox sector and, especially among the ultra-Orthodox, their philosophical approach to challenging issues of science does not carry over to other school systems, largely because of their isolationist approach. Such physical and social isolation was historically adopted by the ultra-Orthodox to limit contact with and infiltration of foreign ideas (which included ideas promulgated by other Jewish denominations) that do not fit into their religious worldview (Liebman 1983; Heilman 2005). In terms of educational policy, this has meant that in Israel the ultra-Orthodox and their independent school system do not affect curricular policy within the Secular and National Religious school systems.

Outside of Israel, a similar isolationist approach has been adopted by both ultra-Orthodox and their school system towards other Jewish denominations. This is very different from the situation in the Christian world, most notably in the United States, where fundamentalists have sometimes successfully gained elected control of school boards leading to critiquing evolutionary theory (http://www.discovery.org/a/9851) and even removing the teaching of (macro)-evolution, as occurred in Kansas in 1999 (http://www.agiweb.org/gap/legis106/evolution.html). Nonetheless, it was noted previously that there is a more subtle influence from the "Haredization" of the modern-Orthodox education system due to the increased number of ultra-Orthodox religious teachers entering that system (Heilman 2005; Helmreich and Shinnar 1998). Such sociological factors could have a stronger influence than the actual content of the science education curriculum. However, there are no studies indicating how that is specifically affecting science education.

Thus, there are challenges to the science education enterprise in the Jewish world. Many Orthodox elements see the challenges posed by the secular philosophy of science as being more of an educational threat than science per se; however, the larger issue of how various groups see secular learning in general, especially secular higher learning, is an indication of how they see science as well.

Certainly Reform and Conservative Jews attend university with no limits to what they study. So too, the modern Orthodox also attend college, although as Soloveitchik already noted in 1994 (p. 64) with "somewhat less enthusiasm" than in previous years. The ultra-Orthodox, who are known historically for their opposition to higher education, are divided in their approaches (Soloveitchik 1994). In the United States, there is recognition of the (economic) utility or even necessity of a degree, and various arrangements have been made to enable ultra-Orthodox to receive such degrees, albeit with (societal) restrictions on what is studied. In Israel, the opposition to higher education is much stronger, although due to the very weak economic condition of most ultra-Orthodox, colleges specifically designated for training this populace have been rapidly developing (Lamm 2010).

Certainly, economic incentive is a path towards increased involvement in secular learning, in general and science, specifically. And in fact it may be the only path that the ultra-Orthodox will accept in the near future. But some in the modern-Orthodox world desire a synthesis represented by a Torah Umadda philosophy because they see the inherent value in secular knowledge and learning. How is this possible?

One possible synthesis is provided by Rabbi Norman Lamm (2010) who has articulated a series of models, based on the philosophies of important rabbinic thinkers of the past. Obviously, to understand and then adopt any of these models requires a deep investment in studying the religious sources and their philosophy, as well as science and its nature.

Indeed, such an investment in learning fits well with one of the recommendations made by the Orthodox scientists interviewed by Dodick et al. (2010) when they were asked how Orthodox Jewish teachers might cope with what they felt were controversial scientific topics, such as geologic time or evolution.

It must be remembered that the Orthodox (high school) science teachers in Israel are adequately educated in science, and many received training in a religious seminary. However, such education rarely deals, systematically, with the possible philosophical conflicts between science and religion. Therefore, the scientists argued that it was important to improve the teachers' understanding of both scientific and Jewish sources that will permit them to settle their internal conflict while providing them with the tools to teach such conflicting subjects with confidence.

Indeed, Lamm (2010) shows how both in the past and today confusion has been created by the lack of understanding about the Jewish philosophical approaches to all secular learning. Moreover, he even shows how traditions that normally would never be considered to be in a Torah Umadda world (specifically, his "Hassidic" model) can be designed to create a synthesis between Judaism and science.

Although knowledge is a primary tool, the Jewish education world is a hierarchical system, especially among the Orthodox, in which teachers must answer to a series of authorities including rabbis, administrators, and parents. Thus, teachers feel more comfortable if they have experts upon whom they can rely (scientists, rabbis, and texts) which allow them to teach scientific issues that are considered to be challenging. Unlike academic scientists, teachers have less freedom to express controversial notions in science or religion, nor are they as well trained in science. Thus, their desire to have a support network of rabbis and scientists who can deal with this conflict is understandable.

This approach also has support from a previous science education study in which Colburn and Henriques (2006) interviewed a group of eight Christian clergymen for whom evolution and religion were compatible and who also believed that Scripture was not meant to be understood, literally. Based on their findings, Colburn and Henriques (2006) suggested that the science education community might find in the educated clergy an articulate ally in helping citizens better understand contentious issues surrounding science and religion.

Because they are not constrained by authority, the scientists interviewed by Dodick et al. (2010, p. 1541) instead recommended that teachers focus on two interrelated issues connected to *application* and *education* to deal with possible conflicts. *Application* is connected to how scientists see religion and science possibly integrating; by *education*, the scientists were referring to how they would like to see the conflict being taught.

Concerning application, the scientists showed a divergence in their choice of philosophies, with the two dominant approaches being the parallel and explanatory approaches. These philosophical differences fit well with application in that some of the scientists favor an approach which emphasizes the points integrating science and religion (comparable to the explanatory approach); in contrast, some of the scientists would rather avoid using science in building religious understanding (comparable to the parallel approach), as the use of science in this way resonates with a fundamentalism with which they don't identify.

Regarding "education," some of the scientists which Dodick et al. (2010) surveyed emphasized critical understanding of learning materials dealing with this conflict. Moreover, some of the scientists desired to see issues of conflict being taught pluralistically by showing students the different philosophical approaches in science and religion that deal with this conflict. This suggestion connects nicely with scientists holding either an explanatory or complementary philosophy as they connect between the domains of science and religion. As these approaches are sympathetic to the preconceived desires of the teachers to also bridge the gap between science and religion, this pluralistic approach might be easier for teachers to implement.

Such integration also has support from the literature (Jackson et al. 1995; Shipman et al. 2002; Smith and Siegel 1993). For example, Jackson and colleagues (1995, p. 605) noted that the current treatment of controversial scientific topics in schools, such as the evolution of humans, is independent of any other way (including via religion) that a student or teacher might seek answers to such topics. They argue that "Scientists and science teachers cannot continue to see themselves as participating in an epic struggle to eradicate mystical superstition and hasten the irresistible ascendancy of materialistic naturalism."

What is missing from this discussion is empirical research. As was seen, much of the education research concerning Judaism and science have focused on the attitudes of students, teachers, and scientists, mostly within the Orthodox world, towards issues of controversy, such as evolution. Future work needs to be more expansive in widening its perspective to other denominations within Judaism[27] and other branches of the sciences. Moreover, for those issues that challenge religious sensitivities much more research must be invested in testing different models of instruction, based on the philosophical approaches that have developed in Judaism. Selya's (2006) work shows that in the modern-Orthodox world, schools have already adopted a number of instructional philosophies for dealing with such controversy; however, research has not yet been conducted to determine their effectiveness. If the goal of Jewish educators is to attain some sort of balance between the world of science and Judaism, then these next steps are crucial.

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[27] We could reference only one paper concerning the interaction between science education and Judaism from a non-Orthodox perspective. Authored by Rabbi Laurie Green (2012), who comes from the Reform movement, this policy paper argued for greater integration (similar to the explanatory approach) between religion and science studies for students belonging to the Reform movement.

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Chapter 55

Challenges of Multiculturalism in Science Education: Indigenisation, Internationalisation, and *Transkulturalität*

Kai Horsthemke and Larry D. Yore

55.1 Introduction: Philosophy, Transfer, and Transformation in Education

The central purpose of this chapter is to position the indigenous–Western knowledge debate within the context of contemporary philosophical views of science and pedagogical insights into science learning and teaching. This will be done by providing a respectful, honest, and straightforward commentary on the strengths and weaknesses of including indigenous knowledge and wisdom (IKW) about nature and naturally occurring events in school science programs. The prior debates between traditionalists, modernists, and postmodernists about the issue have been unproductive. The conflict resolutions that were seeking binary judgements of *good* or *bad* and *science* or *pseudoscience* have not fully reflected the realities of world and science classrooms. These debates have neither considered the sociopolitical and social justice influences nor provided learners with opportunities to engage science without being misinformed about what they were learning—let alone its ontological assumptions and epistemological beliefs. IKW about nature and naturally occurring events is different from Western modern science (WMS), but each has personal value within the parallel worlds of interpersonal-/place-based and public/generalised knowledge systems.

Philosophy might be claimed, cautiously, to be one of the deliberative and critical resources that ought to be brought to bear on questions of accessibility and relevance and on the transfer and transformation of educational systems, knowledge, concepts, and practices—if such processes are to be justifiable, consistent, and effective.

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'Cautiously', because the contribution that philosophy can offer is likely to be modest—for at least two reasons. First, philosophy is only one of the deliberative and critical resources relevant to educational transfer and transformation. Second, deliberation and criticism may be necessary but are not sufficient for the justifiability, consistency, and effectiveness of the processes in question; there are vast and significant contingencies in context and practice that are likely to remain decisive (McLaughlin 2000; Schily 2009).

Over the last 50 years, pedagogical insights into this debate about science education, teaching, and learning have been based on a changing array of learning theories—behaviourism, cognitive development, cognitive psychology, and learning sciences. Based on an integration of cognitive psychology, linguistics, philosophy, and pedagogy, the most recent dominant stance has promoted a learner-activated and learner-controlled meaning-making process that combines prior knowledge, sensory input, interpersonal interactions within a sociocultural context, and intrapersonal reflections within *self*. However, this interpretation of learning might conflict with some philosophers' view of the nature of science.

A promising approach to establishing the appropriate contribution of philosophy to science education in this regard is arguably to focus on the embeddedness of philosophical considerations in many concerns and processes driving transfer and transformation (McLaughlin 2000). Many of these contain, to a greater or lesser extent, concepts, beliefs, values, assumptions, and commitments that—although they themselves may not be of a directly philosophical kind—can be subjected to philosophical scrutiny and analysis. In considering the issue in this chapter, a philosophical distinction might be drawn between worldview and critical activity. Unless seriously mentally impaired, everyone has a worldview (e.g. thoughts or ideas, views or opinions about one's own life and one's place in nature, natural events, and about the world, life, and nature in general); consequently, there exists a multitude of frequently competing and conflicting worldviews. When applied to knowledge about nature and naturally occurring events, people's views range from folklore, religious, indigenous, to scientific. Each can be personally useful, but they should not be confused, confounded, or equated (National Research Council [NRC] 1996).

However, is WMS merely one such worldview among several (Aikenhead 1996; Fakudze and Rollnick 2008)? Alternatively, does it also involve a special type of activity, a process of critical interrogation in which we are concerned with examining and evaluating the ways in which our views, opinions, thoughts, or ideas about the world, life, and nature in general are or have developed (epistemology) and are explained (ontology)? In other words, this involves critical reflection on our ontological and epistemic assumptions, the implications of our views, and the problems that have to be considered in order to reach these conclusions. Even if worldviews 'are culturally validated presuppositions about the natural world' (Aikenhead 1996, p. 4), this does not necessarily mean that that they are equally valid and congruent in terms of epistemology and ontology (Yore 2008), which does not discount their practical and personal value.

A further contribution that philosophy can make concerns the analysis of knowledge and the grounds for knowledge claims, in science education as elsewhere. The debate is between those who treat science and scientific knowledge as a 'cultural enterprise' and those who attest to the 'universality of science' (Stanley and Brickhouse 1994, p. 9). Many people would agree that some folklore about agriculture, meteorology, and navigation is laypeople's well-based expressions of fact, while other folklore in these areas is deemed myth or fancy. Religious-oriented statements about nature and naturally occurring events based on only faith may be of great personal value, but they generally lack the ontological features and epistemic means to be tested and validated using empirical evidence, standardised means, and accepted processes set by scientific communities. There is debate about whether science should be used to test one's religious beliefs, with some maintaining that religious claims about the natural world and its processes (evolution, faith healing, etc.) should be amenable to normal scientific appraisal. The more difficult issue is the consideration of IKW about nature and naturally occurring events, where claims were place based and developed over time using reasonably rigorous epistemologies and oral traditions, but the ontology allows a hybrid explanation of spiritualism and physical causality (Snively and Williams 2008).

55.2 Indigenisation and Internationalisation

The IKW–WMS deliberations need to be placed within the context of worldwide sociopolitical, economic, and social justice influences and efforts. With rapid changes in recent decades of scientific and technological advances, transnational mobility, communication and travel, economic connectivity and dependencies, and—even more recently—increasing democratisation of societies, it comes as no surprise that corresponding changes have occurred and continue to occur in education. These changes concern not only how education, its nature, and its aims are or will be conceptualised but also the very transfer and transformation of educational systems, knowledge, concepts, and practices.

The biggest challenges facing science education have arguably been accessibility and relevance to mainstream boys and girls; these challenges have become more pronounced with the increasingly multicultural nature of teaching and learning environments. How does one render accessible a discipline that has often been viewed as unnatural, difficult, and the intellectual playground of a select, gifted few? How does one instil in students a sense of relevance of science to their lives and experiences, especially if teaching and learning take place in a language and cultural context other than their home language and culture? Many people can remember the shock of entering primary school after years of the free, informal, and unstructured experiences of early childhood to the middle-classed, formal, and structured classroom. Your non-standard forms of the dominant language were not allowed; *stuff*, *ain't*, other colloquialisms, or localisms were deemed inappropriate language. *The gods bowling* as an explanation for thunder was replaced with an abstract idea about a sonic boom caused by rapid thermo-expansion of the atmosphere associated with a static electrical discharge—lightening. This culture shock would be magnified by powers of ten for nondominant language speakers and underserved or underrepresented students who entered the new culture and language environs.

There have been a variety of responses to the transformational implications of globalisation for education and, in particular, for higher education. Chief among these are the drives toward indigenisation, on the one hand, and toward internationalisation, on the other. The radical, extreme versions of these approaches reject any claim to validity or legitimacy by the rival approach. Thus, radical indigenisation involves a back-to-the-roots traditionalism and nationalism that more often than not are inspired by negative effects of the colonial experience and the need for political consolidation or cultural restoration. Globalisation is nothing new; its roots are in the historical explorations and immigrations of the fifteenth and sixteenth centuries when adventurers or refugees picked up their place-based cultures, languages, knowledge claims, and technologies and moved to a new place. It has continued at a more rapid pace today with mobility of populations leading to many free-choice immigrants—such as the two authors of this chapter. Traditionalism and nationalism are forms of sociopolitical priorities designed to conserve or restore cultural identity or forge a national identity.

The Māori Nation's successful efforts to establish the Putaiao curriculum in Aotearoa New Zealand to address colonialism (McKinley and Keegan 2008) and the First Nations' continuing efforts at linguistic and cultural restoration/conservation in Canada to address the social justice ills of residential schools (Snively and Williams 2008) are readily documented examples. Like most political and democratic endeavours based on majorities, not all people involved agree with the fundamental premises. Webb (in press) found that many parents did not want their traditional language and IKW to be the medium and focus of science instruction in South African schools; instead, they supported the English language and WMS curricular mandates with some consideration of IKW. None of the transfer and transformation issues and solutions to this point has considered how people learn—other than that the target learning content needs to be relevant to the target learners. Clearly, many people involved in this debate still adhere to the passive transmission model (i.e. knowledge is passed from teacher to learner, 'teacher directed') rather than the more contemporary interactive-constructive interpretations (i.e. shared student-teacher directed) that involve accessing, engaging, and challenging prior knowledge and supporting learners as they make meaning, store these new ideas in existing knowledge structures, or reorganize knowledge structures to accommodate discrepant ideas (Henriques 1997; NRC 2000, 2007).

Indigenisation involves what Wolfgang Welsch, a cultural theorist, has referred to as the 'return of tribes' (Welsch 2000, p. 349) and may be interpreted as a reaction against globalisation and colonisation. Given the historical, political, and socioeconomic background of exploitation and oppression that motivates and explains indigenisation, the eagerness of people to return to what they perceive to be the sources of their cultural identity—their roots—is perfectly understandable. While this desire to return and to reembrace local values and indigenous traditions is not implausible, the move toward indigenisation has produced some collateral damage. Compounded by problems emanating from unhelpful immigration legislation and bouts of xenophobia (violent actions against foreigners), there has been no transfer, exchange, or mobility on the African continent comparable to that within, or produced by, European Union (EU) member states' secondary and higher education. Instead, the net result has been a marginalisation of Africa, not only of the continent as a whole but also within Africa in terms of increasing isolation of sub-Saharan African countries from each other. Indeed, these policies of 'indigenisation may exacerbate existing societal divisions and lead to new forms of intolerance and discrimination' (Andreasson 2010, p. 427). The reverse racist rhetoric and growing Zulu nationalism as an example of internal dislocation has been highlighted by Chetty (2010). Furthermore, there is the real danger that indigenisation in science education may mislead students and ill prepare them for future higher studies and careers in science, technology, and engineering.

By contrast, radical internationalisation envisages the spread of a universal, more or less monolithic, educational, and socioeconomic culture and tends to ride roughshod over local indigenous histories, values, beliefs, and cultural ways of knowing and explanatory traditions about IKW (Auf der Heyde 2005). Furthermore, such approaches may not engage students' actual prior knowledge, beliefs, and values about science and technology—thereby disenchanting more indigenous and culturally diverse students from actually learning about nature and naturally occurring events from a scientific perspective.

It is evident that neither position holds much promise for science and science teaching and learning. While the former errs in favour of increasing insularity and self-marginalisation, the latter errs in favour of dogmatic homogenisation and lack of regard for difference and diversity. More seriously still, apart from manifesting an essentialist conception of culture and identity, both perpetuate a cycle of disregard, disrespect, and intolerance, with ever-increasing ossification of the opposing fronts and polarisation.

Depending on one's sympathies, it is easy to eulogise one's preferred orientation by pitting it against a straw person that is swiftly and summarily dismissed. Consider, for example, Aikenhead's characterisation of First Nations knowledge of nature as contrasted with Western scientific knowledge:

> Aboriginal knowledge about the natural world contrasts with Western scientific knowledge in a number of ways. Aboriginal and scientific knowledge differ in their social goals: survival of a people versus the luxury of gaining knowledge for the sake of knowledge and for power over nature and other people. They differ in intellectual goals: to co-exist with mystery in nature by celebrating mystery versus to eradicate mystery by explaining it away. They differ in their association with human action: intimately and subjectively interrelated versus formally and objectively decontextualised. They differ in other ways as well: holistic First Nations perspectives with their gentle, accommodating, intuitive, and spiritual wisdom versus reductionist Western science with its aggressive, manipulative, mechanistic, and analytical explanations (Aikenhead 1997, pp. 5–6).

Elsewhere, Aikenhead listed the following attributes characterising the 'subculture of science': 'mechanistic, materialistic, reductionistic, empirical, rational, decontextualised, mathematically idealised, communal, ideological, masculine, elitist, competitive, exploitive, and violent'.[1]

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[1] See Aikenhead (1996, pp. 9 & 10, 1997, pp. 2 & 5, 2001, pp. 11 & 12). Similar attributes of science were purported by Bishop (1998, pp. 200, 201, 210) and Witt (2007, p. 227).

It is not difficult to sympathise with the concerns that underlie advocacy of IKW projects, but it must be ensured that any contrasts of WMS and IKW about nature and naturally occurring events are based on accurate, informed views about the ontological and epistemic aspects of both knowledge systems. Loving (2002) mapped views of science on an ontological–epistemic plane, which led Yore et al. (2004) to identify three general clusters of views (traditional absolutist–realist, modern evaluativist–naïve realist, and postmodern multiplist–idealist) as anchor points for interviews with scientists that delved into their beliefs about their research enterprise. They found that although some scientists use the metalanguage of and identify with the traditional view, most scientists agree with the description of the modern view; a few scientists, mainly from the newer hybrid biosciences, lean toward the postmodern view. However, at the practical and historical perspective, people must be aware that Western knowledge, science, technology, and rationality have led to, or have had as a significant goal, the subjugation of nature; thus far, it has been devastatingly efficient.

The pursuit of nuclear energy (Fig 2005), wholesale deforestation, and the destruction of flora and fauna are arguably deplorable and irrational or, at least in hindsight, questionable applications at times and in certain places. Similarly, apart from being ethically suspect, factory farming of nonhuman animals for human consumption and, especially, vivisection are also examples of bad science (Horsthemke 2010). However, many of these examples used in defining *whose* science and knowledge systems in the modern–postmodern debates about the North–South divide may be more technological rather than strictly scientific (Good 1996; Harding 1991, 2011). Clearly, the definitions of technology as design or as applied science change these debates and claims. Wolpert stated, ‘Much of modern technology is based on science, but this recent association obscures crucial differences and the failure to distinguish between science and technology has played a major role in obscuring the nature of science’(1993, p. 25). The ‘central distinguishing characteristic between science and technology is a difference in goal: The goal of science is to understand the natural world and the goal of technology is to make modifications in the world to meet human needs’ (NRC 1996, p. 24). However, the disparagement and belittling of indigenous peoples’ practices, skills, and insights has, to a large extent, been arrogant and of questionable rationality. If honest engagement is desired in education and public awareness activities, it will require recognising cultural values, lived experiences, and prior knowledge and beliefs of those being engaged. Finally, current attempts by industrial, first-world nations to colonise or appropriate for commercial gain indigenous people’s knowledge, practices, skills, and insights in the name of globalisation and worldwide development are exploitive and contemptible.

People hold many misconceptions and myths about the nature of science regarding the singularity of the scientific method, hypotheses as educated guesses, evolution of hypotheses and theories growing into laws, absolute truths based on accumulated evidence, procedural nature of inquiry, scientific enterprise can address all questions, scientists as supernatural people, all science is experiment-based, and all science claims are peer-reviewed to ensure honesty (McComas 1996). Therefore, a pro-Western/Eurocentric perspective might mislead one to characterise the differences as follows: the celebration of knowledge as intrinsically valuable versus the view of knowledge having no value in itself; reliance on a critical, rational scientific method versus superstition, magic, witchcraft beliefs, ancestor worship, and unquestioning obedience toward traditional authority; commitment to universal applications and solutions versus ethnocentrism and thoroughgoing cultural and epistemological relativism; and the value of scientific evidence versus faith and reliance on revelation. These binary positions have led to polarised controversy and winner-takes-all solution strategies, whereas in the pragmatic worlds of science education and science teaching, the greater good might lie or involve moving between these poles—two-way border crossing with mutual honour and respect (Chinn et al. 2008).

55.2.1 Knowledge Claims and Justification

If anything qualifies as science, there are certain criteria that must hold. It needs, at minimum, to involve reference to regularity, observation, description, explanation, prediction, and testable hypothesis. If it does not meet these criteria, it is not ‘science’, as commonly understood to be people’s endeavour to search out, describe, and explain patterns of events in nature and naturally occurring phenomena where the claims are based on evidence and are generalisable and the explanations involve physical causality (Good et al. 1999). When only the epistemic beliefs and practices are considered, there is little difference between traditional IKW and WMS; but when the ontological requirements are considered, the two knowledge systems demonstrate critical differences (Yore 2008). Both indigenous and scientific epistemologies have well-established, rigorous systems and routines of observations, interpretative frameworks, and feedback loops to make, update, and revise descriptions of patterns and knowledge claims (Snively and Williams 2008). However, on the ontological dimension, indigenous explanations involve a mixture of spiritual and physical cause–effect mechanisms, while scientific explanations are limited to physical causality devoid of mysticism, magic, and spiritual causes.

With regard to scientific knowledge, one generally distinguishes between two kinds: practical knowledge and theoretical knowledge. The former denotes craft knowledge, skill, ability, practice, or custom taught or passed down from one generation to another without evidence, justification, or explanation. Some historical technologies and practices within skilled trades demonstrate such characteristics. Apart from necessarily incorporating belief, theoretical knowledge involves commitment to truth and justification (i.e. scientific evidence; Haack 2003). In other words, a person knows that something is the case if she believes that it is so and she has adequate evidence for believing that it is. Science, as well as being about inquiry, is about evidence-based empirical argumentation. Toulmin’s (1958) pattern and elements (data, backings, warrants, evidence, claim, counterclaim, and rebuttal) were used frequently to describe and evaluate the quality of an argument. Adequacy, however, cannot be determined by a checklist of elements; it must be determined by the kind, degree, and context of evidence (Gott and Duggan 2003; Tytler et al. 2001; Walton 2005; Walton et al. 2008).

Different kinds of evidence pertain to the different sciences, natural as well as social. They include observation, sensory experience, oral and written testimony, and deductive and nondeductive (inductive, abductive, and analogical) reasoning. As far as the requisite degree is concerned, minimal evidence is clearly not enough, while conclusive evidence is usually not available. Normally, other than in mathematics and deductive logic, we accept evidence that is less than conclusive, that is, reasons that are nonetheless compelling within an evaluative context (argument–critique–analysis). These science and engineering practices were recently included as a central part of the new framework for science education regarding scientific inquiry and technological design, which will influence the next generation of science education standards in the United States of America (NRC 2012).

Yet, what makes evidential reasons compelling has partly, and importantly, to do with context—not only the particular scientific context but also, for example, the problem space, the environment, the cultural and social biography, and the reasoning level of the person making the knowledge claim (Aikenhead 2005). Considerations of context determine leniency or stringency, and ascription of scientific knowledge reflects the social component of knowledge, which reveals that attributions of knowledge are context sensitive (Cohen 1986). Scheffler argued that the idea of *suitability* is:

> [A] matter of appraisal, involving standards of judgment that may differ from age to age, from culture to culture, and even from person to person. The variability of such standards does not, however, imply that assessments of knowledge are arbitrary or that the would-be assessor is somehow paralyzed. He needs to assess in accord with his own best standards at the time, but he may hold his assessment subject to change, should he later have cause to revise these standards (Scheffler 1965, p. 57).

He pointed out that these standards might be applied more strictly in some cases, more approximately in others, 'thus giving rise to multiple interpretations of *knowing*' (p. 58). Therefore, the justification component permits some leeway toward a multiplist view of science where multiple interpretations of datasets are expected as the interpreters apply their lived experiences and individual interpretative frames, but the alternatives will be evaluated in the public arena of the involved science community. What counts as suitable justification in the case of a young child or person from a remote rural area—with limited opportunities, resources, or access to information—differs from that required of an older, more mature person from an industrialised, technologically advanced, privileged, and urban background. Scheffler noted the implications for education when he stated, 'As the child grows and as his prior learning takes hold, his capacity increases, allowing us to tighten the application of our standards in gauging his current performance' (p. 57). Thus, with this growth in the child's cognitive capacity, 'the same subject may thus come to be known under ever more stringent interpretations of *known*' (p. 57).

Yet, in all the various cases, the justified belief must be true and present. In the absence of truth, one cannot meaningfully speak of, or ascribe, knowledge. Scheffler suggested a subtle shift from examining beliefs to examining the *contexts* in which beliefs were advanced as knowledge-claims when he distinguished the question concerning justification of a belief from the 'question of *appraisal of the believer* …. To speak of the right to be sure is, in the present context, to appraise the *credentials* of belief from the vantage point of our own standards; it is to spell out the attitude of these standards toward specific *credentials* offered for a belief' (p. 64).

Like Scheffler, Cohen (1986) argued that the suitability of justification, or having good reasons, depends on the relevant epistemic community. He advanced his argument through an analysis of what it means to have good reasons for believing something. The concept of *defeasibility* is crucial. One's reasons for believing something are *defeasible* if there is something else that could count against them, that is, something that could defeat them or undermine their feasibility. According to Cohen, we can say that someone (e.g. a 6-year-old) has good reasons if, given her reasoning ability, it is epistemologically permissible for her to believe that something is the case. Scheffler would be inclined to apply the standards of justification more leniently in the case of the 6-year-old and more strictly in the case of the 16-year-old. Both the 6-year-old and the 16-year-old may form a justified true belief that the table they see in a darkened room is red. However, when they are informed about the presence of a red light bulb in the room (hidden from their view), the younger child will hardly be able to appreciate the significance of the presence of this *defeater*. Therefore, if she continues to cling to her belief that the table is red, we would normally credit her with sufficient justification for her knowledge claim. On the other hand, if the older child fails to see anything wrong with clinging to her belief, we would normally be more reluctant to credit her with knowledge that the table is red. What passes for sufficient or adequate justification, then, will differ, and a progression of plausible reasoning would be established.

The important point for science teachers is that what counts as a good reason depends on who is giving the reason and in what context. One of the responsibilities of a science teacher is to assess learners' knowledge *of*, *for*, and *as* learning in ways that are sensitive both to their level of understanding and to the context of assessment—accountability (of), empower learning and inform teaching (for), and stimulate learning (as). Another related responsibility is to develop the learners' grasp of the intersubjective standards of different learning areas, such as common core learning outcomes in English, social studies, science, and technical subjects (National Governors Association Center for Best Practices and Council of Chief State School Officers 2010) and cross-cutting concepts with science and engineering domains (NRC 2012). In Cohen's terms, to help learners move from a level of reasoning that provides *subjectively evident* grounds for believing something to a level that provides *intersubjectively evident* grounds for beliefs about conceptual systems and socioscientific issues.

The concept of having good reasons is not without ambiguity. A person can have subjectively good reasons (i.e. reasons that are clear and convincing to her, given her level of understanding) or intersubjectively good reasons (i.e. reasons that are clear to her and that comply with the standards of reasoning of the social group to which she belongs). How are these different applications of justification relevant to the concept of knowledge? When is an educator entitled to say that a learner knows something in the sense of knowing that in a deep way? To put the question more formally: Under what conditions may a teacher attribute knowledge to a learner?

Scheffler urged that someone possesses suitable justification when that person possesses reasons for the quality of understanding: 'In saying he knows, we are not merely ascribing true belief but asserting that he has proper credentials for such belief, the force of which he himself appreciates' (1965, p. 74). Scheffler's and Cohen's arguments imply that even if a learner has subjectively good reasons for believing something to be true, she does not have knowledge unless she also has intersubjectively good reasons for a true belief or knowledge claim. One of the tasks of effective science teaching is to assist learners to acquire the relevant concepts and intersubjective standards of justification for evidence-based empirical arguments. Here, one's sense experiences must be reliably connected with the world, one's sense organs must be intact, and one's reasoning must be correct. An analysis of good reasons indicates why reference to them is context sensitive and why neither reasoning nor our sensory experiences are infallible. Nonetheless, if they are generally reliable sources of justification, the reasons they produce might be called *intersubjectively certain*. Cohen stated, 'Reasons can be permissible grounds for belief, relative to that standard, even though they are not ideally correct'(1986, p. 575). Essentially, both the beliefs and the justifications (reasons) given for them, but not their truth, may depend on particular social and cultural contexts or circumstances. Therefore, people can acknowledge differences in cognitive resources, skills, and opportunities without thereby having to commit to epistemic relativism.

In Plato's cave parable, whatever the enlightened person knows about reality stands in stark contrast to the (majority) view that the prisoners in the cave claim to know is reality. The cave parable indicated that knowledge is ambiguous between various concepts, when each is based on a different standard. Is knowledge context dependent? Scheffler's and Cohen's arguments suggest that it may be better to say that attributions of knowledge are context sensitive. The term *context sensitive* does not offer an open invitation to or endorsement of epistemological relativism. It is important to note that, in terms of the present definition, while belief and what counts as evidence may vary from individual to individual, society to society, and culture to culture, truth does not.

The present account acknowledges that people do not have the same cognitive resources, skills, and opportunities. They do not all act or operate in the absence of constraints. Their situations are characterised by different levels of expertise, by different opportunities to access and gather information, by different levels of cognitive maturity and training, and by considerable differences in available time and deadlines. Goldman cautioned that a 'social epistemology for the real world needs to take these constraints into account' (1991, p. 233). So, when Aikenhead argues that 'the knowledge, skills, and values found in the typical secondary science curriculum have been widely criticised throughout the world for being isolated and irrelevant to everyday events that affect economic development, environmental responsibility, and cultural survival' (1997, p. 7), one might respond by acknowledging the need for science education and education in general to be anchoring in and connected to the real world and to each other.

55.2.2 Politics and the Knowledge Enterprise

A central theme of this chapter has been a social justice motive within a rigorous epistemological and ontological stance applied to IKW, WMS, science education, and science teaching. Occasionally these motives can run opposed to one another, but they need not. Worldwide there have been efforts to rationalise educational and economical energies and programs across diverse cultural and ethnic communities. In June 1999, the EU ministers of education stated in the Bologna Declaration:

> *A Europe of Knowledge* [emphasis added] is now widely recognised as an irreplaceable factor for social and human growth and as an indispensable component to consolidate and enrich the European citizenship, capable of giving its citizens the necessary competencies to face the challenges of the new millennium, together with an awareness of shared values and belonging to a common social and cultural space (European Commission 1999, p. 1).

Among the central concerns of the Bologna Declaration were the transformation of educational systems and the transfer of educational experiences and knowledge, as well as the possibility of active and meaningful engagement across historical, social, cultural, and linguistic borders. The Bologna Declaration was a pledge by each of the 29 signatory countries. In the explanation prepared by European university administrators, the following points were listed:

- [A] commitment freely taken … to reform its *own* higher education system or systems in order to create overall convergence at European level. …
- The Bologna process … is not a path toward the "standardisation" or "uniformisation" of European higher education. The fundamental principles of autonomy and diversity are respected.
- The Declaration reflects a *search for a common European answer to common European problems*. The process originates from the recognition that in spite of their valuable differences, European higher education systems are facing common internal and external challenges related to the growth and diversification of higher education, the employability of graduates, the shortage of skills in key areas, the expansion of private and transnational education, etc. (Confederation of EU Rectors' Conferences and Association of European Universities 2000, p. 3).

In addition,

The Declaration specifically recognises the fundamental values and the diversity of European higher education:

- It clearly acknowledges the necessary *independence and autonomy of universities*; …
- It stresses the need to achieve a common space for higher education within the framework of the *diversity of cultures, languages and educational systems* (p. 6).

This agreement attempted to make the transfer of university experiences, course work, and certifications possible and to expedite the movement of students and professionals among the various jurisdictions of the EU member states. These efforts within the founding EU member states have gone reasonably well, but there have been some concerns with the blending of different university systems, traditions, and conventions. The long, historical, collaborative efforts in science, technology, and mathematics in the academies and research institutions have helped the rationalisation efforts of the Bologna Declaration. The real test will be the integration of new members of the EU without long records of collaboration and similar traditions. Will this effort in Europe influence similar reform efforts in other regions of the world where knowledge systems, epistemologies, and ontologies might differ drastically, like Africa?

55.3 Transformation in Africa

Finger (2009) suggested that people should disregard the new system for the inherent value of knowledge (as contrasted with its purely instrumental value) and this would provide a similar motive and advocacy of *Africa of knowledge* as that which drives toward a *Europe of knowledge*. This pertains not only to political leaders opening tertiary institutions in recently liberated African countries in the 1950s and 1960s and potential changes to established knowledge-building institutions resulting from the Arab Spring but also and especially of contemporary theorists and academics emphasising the need for secondary and higher education to develop an African identity. Makgoba stated:

> The issue of pursuit of knowledge for its own sake and the so-called standards have … become contentious factors around the African university. … The pursuit of knowledge for its own sake has been one of the cornerstones of university education; but is there such a thing as knowledge for its own sake today? Knowledge is a human construction that by definition has a human purpose. Knowledge cannot be sterile or neutral in its conception, formulation and development. Humans are not generally renowned for their neutrality or sterility. The generation and development of knowledge is thus contextual in nature (Makgoba 1997, p. 177).

Does this mean that funding and support for curiosity-driven inquiries (science) will be threatened and replaced by this call for mission-driven inquiries (technology/engineering)?

That knowledge ascription and justification have a crucial contextual component is surely not in doubt (Horsthemke 2004), but this does not mean that the pursuit of knowledge must be described and explained in consequentialist or constructivist terms. It might be the *object* of knowledge that is and continues to be the legitimate cornerstone of secondary and higher education. 'The global competition, the involvement of industry in universities, and the social, economic and political pressures of modern society have made the [pursuit of knowledge for its own sake—curiosity-driven pursuits] obsolete. … The pursuit of knowledge and the truth with a purpose and social responsibility [mission-driven pursuits] is what universities are about' (Makgoba 1997, pp. 181–182). Surely, setting up a commission like the Truth and Reconciliation Commission also involved a noninstrumental understanding of knowledge and truth (Horsthemke 2004). If they had an exclusively instrumental function, then substituting them would be entirely permissible—say, with an amnesia drug—as long as the desired end effect or outcome was the same. With regard to the traditional roles that universities throughout the world have in society, Makgoba considered the social responsibility of knowledge systems when he stated:

> [The] preservation, the imparting and the generation of knowledge. … It is important to recognise … that the imparting of inappropriate or irrelevant education, even of the highest calibre, would … lead to a poor and ineffective product. Thus, university education has to be relevant not only to the people, but also to the culture and environment in which it is being imparted (Makgoba 1997, p. 179).

Without doubt. The trick, of course, is to avoid an education system that is impoverished as a result of excessive concerns with people's culture and user-friendliness. Makgoba's comments are equally applicable to elementary and secondary education and especially to science education and science teaching.

However, the resolution of this pedagogical issue in learning and teaching science can place politicians, philosophers, and educators at odds. Some politicians have stressed that the social justice issue overrides any considerations of the nature of science and how people learn science. Some philosophers have questioned the validity of constructivism applied to the scientific enterprise (Matthews 2000; Nola 1997; Suchting 1992), while science educators advocate an interpretation of how people learn that has a constructivist flavour (NRC 2000, 2007). Henriques (1997) investigated the conceptual mix of science and pedagogy (behaviourism, cognitive development, and learning sciences) within the sociocultural contexts of schools and found that inquiry teaching within the constructivist learning perspectives ranged from information processing, interactive constructivist, social constructivist, or radical constructivist. She considered the underlying factors (i.e. nature of science, ontological, epistemological, cognitive, pedagogical, discourse/language influences, and realities of classrooms) in these interpretations and found little support for the strong sociocultural and radical constructivist approaches, some lingering uses of behavioural-based information processing, and sizeable support for the centralist approaches and modified learning cycle (engage, explore, consolidate, assess).

55.3.1 Africanisation and Afrocentrism

Nowhere have indigenisation and internationalisation efforts been more apparent than in Africa—a continent of diversity. Africanisation (continent-wide/global perspective) and Afrocentrism (cultural/ethnic perspective) have included radical endorsements, which tend to reject any outside (e.g. colonial, Western, Northern, European, Eurocentric, etc.) influence and also segregationist forms of nationalism (such as some trends manifested in the former Soviet Union, Yugoslavia, etc.). What they arguably share, apart from an intense belief about internal homogeneity and an equally strong rejection of heterogeneity is an instrumental usage of the concept of indigeneity. Indigenisation was not only seen as an effective instrument for political persuasion, mobilisation, and justification but also as a tool in transformation, educational, socioeconomic, and cultural aspects of the larger issue and national goals. As such, it becomes symbolic and may actually produce a virulent form of the 'ethnicisation' of education, politics, and the economy (Andreasson 2008, p. 7).[2] A characteristic of this approach, one of its 'normative entanglements', is the rejection of Eurocentrism, which is linked to an express sympathy with the ethnocentrism of non-European cultures (Cesana 2000, p. 452). Yet, to respond to Eurocentrism by embracing Afrocentrism is relevantly like responding to school-ground bullying with corporal punishment or to murder with capital punishment. Motivational reasons do not amount to justification of the prescribed solution in any of these cases (Horsthemke 2006).

So much for the caricatures. There are obviously more nuanced versions that deserve correspondingly serious consideration. Thus, in the instance of indigenisation, there is an emphasis on the local that nonetheless acknowledges the significance, if not the inescapability, of the global. 'We [Africans] have to construct our own epistemological framework from which we can explore ideas and build our own knowledge. … Africans must create our own paradigm from which we can also dialogue meaningfully with Europeans' (Masehela 2004, p. 11). A vice chancellor of the University of KwaZulu-Natal in South Africa maintains:

> It is the duty of academics and scholars to internationalise, articulate, shape, develop and project the image, the values, the culture, the history and vision of the African people and their innovations through the eyes of Africans: African people should develop, write, communicate and interpret their theories, philosophies, in their own ways rather [than allow these to be] construed from foreign culture and visions (Makgoba 1997, p. 205).

Moreover, he stated, 'global economic competition is high and unless we develop a competitive high technology economy we face economic ruin, stagnation and under-development, with dire consequences for the impoverished rural and urban communities' (p. 179). While the latter insight is surely correct, Makgoba does not elaborate on the assumption that Africanisation is compatible with internationalisation or with developing a competitive high-technology economy. Furthermore, he appears to use technology and science interchangeably and does not differentiate the ontological and epistemic characteristics of science, technology, engineering, and traditional knowledge systems. Fuller deliberations are needed to establish how an Afrocentric orientation is supposed to cater for the demand, 'as we enter the era of globalisation, … to rethink ourselves anew, and bring in new ideas if we are to be a significant part of the information age and an era of knowledge industries' (Ntuli 2002, p. 66) and with the 'need to develop people and prepare young South Africans for the future and the tough world of global competition' (Makgoba 2003, p. 2). Conversely, in the instance of internationalisation, the emphasis on the global is seen as compatible with or perhaps even requiring an acknowledgement of diversity, difference, and locality/indigenousness. This sociopolitical, socioeconomic, and techno-science problem space requires fulsome and rigorous considerations

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[2] For a thinly veiled endorsement of this kind of reverse racist, indeed ethnocentric orientation, also see Makgoba and Mubangizi (2010), especially the chapter on Leadership Challenges.

and deliberations regarding those involved, ensuring fair distribution of risks and benefits are appropriately distributed across the participants.

There are further, remarkable parallels between the Bologna Declaration and the call for the Africanisation of education: emphasis on the Africanisation of knowledge, teaching and learning, and finding *African answers to African problems*, the endeavour to make the African university internationally attractive and competitive, to establish international respect for Africa's rich and extraordinary cultural and scientific traditions. The major difference is that Africanisation and Afrocentrism emanate less from the political/economic precedent of the African Union and the common objectives of convergence and transnational mobility than from a shared rejection of the European education system and Eurocentrism. While the Bologna Declaration may be interpreted as a call to unity by harnessing Europe's many strengths, the emphasis in Africanisation and Afrocentrism is more on unity as a means of resisting the external economic, cultural, and political influences.

Africanisation is closely associated with educational and institutional transformation and embodies traits of both internationalisation and indigenisation in which the former link may be more controversial. Africanisation of education has a clearly *international* element (i.e. between African nations/nation states), just like Europeanisation of education has been between EU member states. Moreover, the idea of Africanisation of knowledge bears more than a fleeting resemblance to the Bologna Declaration's internationalist reference to a Europe of knowledge. Africanisation binds together a plethora of Saharan and sub-Saharan nations and states. The late Libyan head of state Muammar Gaddafi's vision of a United States of Africa, with himself as Emperor of Africa, may have been a delusional, autocratic fantasy—but at least the first part of it is shared by many people in Africa. This desire for pan-African unity is captured in the frequent appeal to communalism as a typically African value and reference to the essence, identity, and culture of Africa (note the singular).

On the other hand, there is a strong emphasis in Africanisation and Afrocentrism on indigenous, local—as contrasted with, say, global, international, European/Eurocentric—educational knowledge, practices and values. For example, there is a frequent endorsement of African mathematics as ethnomathematics, traditional knowledge about nature and naturally occurring events as ethnoscience, and African knowledge systems as indigenous knowledge systems as opposed to academic or mainstream mathematics and science and world knowledge, respectively. The African *is* the indigene: colonised, exploited, marginalised, and historically excluded from the international mainstream.

A South African report on transformation, social cohesion, and the elimination of discrimination in public higher education institutions stated that 'at the centre of epistemological transformation is curriculum reform—a reorientation away from the apartheid knowledge system, in which curriculum was used as a tool of exclusion, to a democratic curriculum that is inclusive of all human thought' (South Africa Department of Education 2008, p. 89)—later referred to as 'the Africanisation of the curriculum' (p. 91). The report contends that 'resistance to Africanisation is often advanced under the guise of a spurious argument suggesting that the debate is not about privileging Western scholarship, but rather emphasizing the universality of knowledge' (p. 91). It is 'the local context [that] must become the point of departure for knowledge-building in universities [across Africa and, indeed,] the world' (p. 92). However, not all stakeholders and scholars fully endorse an Africanised curriculum and knowledge (Horsthemke 2004; Webb in press).

55.3.2 Cosmic Africa

Efforts to identify and document an African perspective on knowledge about nature and naturally occurring events have taken many forms. The film *Cosmic Africa* (Rogers et al. 2003) documents the journey of South African astrophysicist Thebe Medupe in his mission to connect occidental science and astronomy to the cosmological models of some of the oldest civilisations on earth. Astronomy survives in these ancient societies despite the eroding effects of colonialism and its modern heir, globalisation. Medupe emphasises that astronomy has never just been a science in these cultures, where it is an 'intimate tapestry merging into their prayers, their lives, their dreams and their deaths'.[3] Occidental culture, on the other hand, has separated astronomy from daily experience and turned it into pure science from astrology. Medupe's mission was stated at the very beginning of the film: 'I need to discover whether my science has a place in Africa, and whether Africa has a place in my science.' His journey leads him to the Ju/'hoansi in northeastern Namibia, the Dogon in Mali, and finally to Nabta Playa in the southern Egyptian Sahara, to what is conceivably the site of the first solar observatory (see also Rogers 2007, p. 19).

During his visit to Namibia, Medupe learns not only of Ju/'hoansi reliance on the stars as to when to plant and to harvest as an astro-calendar but many of the stories connected to the sun, moon, and stars:

> One memorable night, Kxau Tami and /Kunta Boo, two elderly shamans, demonstrated how they would throw burning sticks in the direction of a very bright meteor—as they threw the sticks into the air, they uttered swear and curse words which they said would help to divert the meteor's path and thereby prevent its dangerous potential. They believe that bright shooting stars with fiery tails are invested with very powerful !nom (extreme potency) and that they have the potential to cause sickness (Rogers 2007, p. 21).

Medupe's visit to the Ju/'hoansi coincided with a total solar eclipse. He worried about whether he should tell the people about what is going to happen but decided not to; they would want to know how he knows. Instead, he sets up his equipment. When the eclipse happens, people talk about the return of winter and blame the intruder and his equipment: 'The telescope is eating up the sun.' After the eclipse and subsequent reconciliation, Medupe says, 'For the first time, I see how the stars interact with long-held beliefs to affect the way people live. My science and my Africa are beginning to come together.'

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[3] Note that quotations attributed to Medupe in this and following paragraphs are taken from the film's dialogue; hence, no page or paragraph numbers are provided.

This impression was deepened with the visit to the Dogon, whose knowledge of the stars is legendary. Their daily and seasonal activities, routines, and customs are guided, for example, by the appearance of Venus (for which the 'Dogon have a number of different names …, depending on its station in the sky'; Rogers 2007, p. 21), 'Toro Jugo—the Pleiades' (Rogers 2007, p. 20), etc. One of the elders, spiritual leader Annayé Doumbo, claimed, 'In our Dogon way, the man who makes technology is the sorcerer of the sun'. Given the harsh conditions under which they live, to the Dogon, knowing the stars can mean the difference between life and death. Does the elder know that human beings have walked on the moon? 'There is no gate to the moon', is the reply, 'it is not possible for anyone to go there, unless they are the little brother of God'.

The last leg of Medupe's journey was presented as the origin of astronomy, Egypt. However, there was no mention of the innovations and discoveries of the Maya and Aztecs, which can be taken as evidence of the lack of knowledge transmission between continents in the southern hemisphere. In the southern Egyptian desert, near the border of Sudan, he discovered what is conceivably the oldest observatory conceived and constructed by the Nabtans, nomadic pastoralists, now long dead. Predating Stonehenge in England by almost 1,000 years, it consists of stones emanating from a centre, in order to trace the rising and setting of the sun during the year, as well as the passage of the moon and stars. Medupe stated, 'The origin of astronomy, its measuring and predicting is in Africa … Stones took the place that my computer takes now.'

It was Medupe's prime intention to create an African star chart; unfortunately, he and the research team never explored any of the tensions between IKW and WMS worldviews, knowledge claims, and explanations. They seem satisfied with just noting the different perceptions and appear to assume that there is no problem of reconciliation of myth or legend with scientific claims and explanations. At the end of the film, Medupe stated that he has come 'full circle', that his journey has served to (re)unite 'his [postmodern] science' and 'his Africa', without any attempt to account for the contradictions encountered between spirituality and astronomy.

55.4 Reflecting on Attempts to Indigenisation/Africanisation and Internationalisation

Attempts to promote specific geographic, cultural, or ethnic interpretations of knowledge and knowledge construction have encountered problems in the search for truth and wisdom within a global society. Continental landmass or geopolitical boundaries and ethnocultural groupings cannot confine knowledge, especially knowledge about nature and naturally occurring events. Efforts to indigenise or Africanise and internationalise have received philosophical, pedagogical, and practical critiques.

55.4.1 Problems with Indigenisation

Medupe's long-term goal was to develop a database and to set up a formal ethnoastronomy research group. The pertinent questions, for present purposes, were: Does the idea of ethnoastronomy make sense? What, if anything, distinguishes ethnoscience from mainstream, academic science? Is it a spiritual, contextual, or cultural element? The differences between WMS and IKW about nature and naturally occurring events may vary across science domains and between science and technology.

Jegede (1999) emphasised that the local and contextual character of his interpretation of scientific knowledge and truth, in terms of learning and teaching where a 'strong relationship that exists between the prior knowledge and sociocultural environment [of the student. It is] deemed primitive, inferior and unscientific' (p. 120) by/in the 'Western view, especially with regard to science teaching and learning' (p. 123). No wonder, the cynic might question his four fundamental features of the African belief and thought system—belief in a creator/god, belief in life after death/reincarnation, anthropocentrism or the idea that human beings constitute the centre of the universe, and the theory of causality, which 'is the sociocultural cloak the African child takes to the science classrooms' (p. 125)—and their application to knowledge, cognition, or science. Good (2005) expressed sincere concern about mixing scientific and religious habits of mind and related ontological requirements for explanation of nature and naturally occurring events.

Aikenhead and Jegede stated:

> In the culture of Western science, students learn that the refraction of light rays by droplets of water causes rainbows; in some African cultures, a rainbow signifies a python crossing a river or the death of an important [traditional] chief. Thus, for African students, learning about rainbows in science means constructing a potentially conflicting schema in their long-term memory. Not only are the concepts different (refraction of light versus pythons fies") (Aikenhead and Jegede 1999, p. 276).

Aikenhead and Jegede appear to have confounded the ways of knowing as a learning process with the established procedures for doing and knowing science. They were actually, at best, using the contrast to differentiate epistemologies since they have provided little insights into the differences in metaphysics and underlying ontological requirements for scientific explanations. This raises the question: Which of these accounts constitutes science? Traditional African education appears to discourage critical interrogation of received knowledge, wisdom, and practice. In terms of validity and usefulness (explanation limited to physical causality void of magic, mysticism, and spiritualism; prediction and predictive power; etc.), there is no equivalence here—WMS and traditional African IKW are different! However, if Jegede's account was meant to exemplify an initial engagement strategy and 'collateral learning' (which is principally about students holding a multitude of worldviews at the same time), it might be argued that 'traditional thought' or 'explanation' (1999, p. 131) might access and engage students with traditional prior knowledge and experiences; frequently, however, it fails to involve acquisition of facts or truth and, therefore, does not constitute knowledge. For this reason, one might even consider the reference to different epistemologies/ontologies incomplete, inappropriate, or misleading.

In a related vein, le Grange mentioned the *localness* of all knowledge systems: All knowledge is local, 'located/situated and motley (messy situatedness)'. While it makes some sense to say that 'all knowledge systems have localness in common', they also share objectivity and *trans*localness (Le Grange 2004, p. 87). Le Grange would probably concur with Visvanathan's statement that 'Morality, like science, has to be invented individually' (Visvanathan 2002, p. 51). However, this view indicates a basic misconception since neither science nor morality is an individual invention. There is also a disconcerting relativism manifest in views like these. WMS attempts to make evidence-based claims, generalised explanations involving physical causality, and public evaluation where Nature is the final arbiter (Ford 2008). However, some science events and several technologies are place based, which make them suitable engagements for students in these locations.

When Māori scholar Russell Bishop refers to *Kaupapa Māori*, 'the philosophy and practice of being and acting Māori', as an 'orientation in which Māori language, culture, knowledge and values are accepted in their own right' (Bishop 1998, p. 201), this points to a fairly thoroughgoing relativism. He adds a disclaimer: 'It is also important not to ignore the impact of European colonialism by claiming that Māori culture has all the answers. Nor is this to say that *all* knowledge is *completely* [emphasis added] relative' (p. 210). The postmodernist relativist phrase 'all knowledge is completely relative' is troublesome for many philosophers of science, nature of science in education researchers, and curriculum developers as it implies that all claims are equally valid and should not be evaluated for fear of disempowering the people making the claims. Such a position might represent the slippery slope in educational thinking for WMS, public evaluation of science claims, nature as final arbiter, rigorous epistemologies, and restricted ontological assumptions. Application of these relativistic ideas will not allow biologists to differentiate among divine creation, intelligent design, and evolution explanations of changes in living organisms (including humans), which has been the focus of much legal deliberation and scholarly debate.

Relativism as a social justice stance, in particular, is problematic in that one would not be able to compare and evaluate competing knowledge claims. However, many postmodern curriculum theorists welcome this implication as a solution to the disciplinary power structure that disempowered minority scholars and silenced underrepresented voices. Onwu and Mosimege were worried about the gatekeeping mechanisms set up by WMS to determine 'what is to be included or excluded as science' (2004, p. 4). If relativism were true, for the sake of the present argument (i.e. assuming that its truth could be established nonrelatively and that this would not constitute a vicious logical inconsistency), then there would be no epistemic or veritistic grounds for choosing between the claim that rain is the result of a chain of physical cause–effect relationships involving condensing moisture that occurred as a result of evaporation driven by solar radiation and the belief that 'rain can arise at will as a result of human action' and 'the rain by-passes the farm/field of the person who stands while drinking during the ploughing season' (Onwu and Mosimege 2004, p. 7). Most disturbingly, this kind of approach would thwart all scientific inquiry into, or curiosity about, phenomena for which there already exists a traditional, folkloric account or explanation. This barrier to continuous disbelief and inquiry is similarly deterred by an absolutist–realist view of science for established ideas.

55.4.2 Problems with Internationalisation

The critique of internationalisation as a viable, defensible approach to transformation of science education—and the teaching and learning of scientific knowledge, concepts, and practices in non-Western or indigenous societies—was diverse in both articulation and geographical orientation. Bishop has argued that

> [a]ttempts to locate Kaupapa Māori research within the broad framework of international perspectives on *participatory research*, [emphasis added] indeed even to search for a methodology of participation, may defeat the very purpose of Kaupapa Māori research, which is to reduce researcher imposition in order that research meets and works within and for the interests and concerns of the research participants within their own definitions of self-determination (Bishop 1998, p. 210).

Participatory research has a distinct political action function that sets it apart from most educational research approaches. Embracing a First Nations–Aboriginal perspective and referring to transmission and transformation of science education in particular, Aikenhead stated that the 'nature of the transformation [requires] science to articulate with practice' (Aikenhead 1996, p. 29). Elsewhere, he added:

> Science education's goal of transmission runs into ethical problems in a non-Western culture where Western thought (science) is forced upon students who do not share its system of meaning and symbols … the result is not enculturation, but assimilation or "cultural imperialism"—forcing people to abandon their traditional ways of knowing and reconstruct in its place a new (scientific) way of knowing … (Aikenhead 1997, p. 11).

Similarly,

> if … science is generally at odds with a student's everyday world, … then science instruction can disrupt the student's view of the world by forcing the student to abandon or marginalise his/her indigenous way of knowing and reconstruct in its place a new (scientific) way of knowing. The result is assimilation … [which] has caused oppression throughout the world and has disempowered whole groups of people (Aikenhead 1997, p. 4).

Abrams et al. (in press) discussed 'pedagogy of hope' regarding culturally relevant science teaching involving traditional knowledge systems, mathematics, and science. They identified contemporary research findings that outline the successes and failures involved in engaging indigenous students with traditional indigenous knowledge, which have been promoted by the Alaska Native Knowledge Network (http://www.ankn.uaf.edu/) and the Indigenous Science Network Bulletin (http://members.ozemail.com.au/~mmichie/network.html).

Education can inculturate or assimilate students into a specific culture, forcing them to leave behind their home culture, or it can acculturate students into living in two cultures with free movement between these cultures. Many practicing scientists report having both religious and scientific beliefs representing their professional and personal cultures where they strategically move between these cultures as needed. Several science educators have endorsed a two-way bridge or border-crossing analogy for working with indigenous and nonindigenous students in IKW and WMS.

The notion of internationalisation, then, involves the assumption that the worldwide trend of cultures and societies is toward increasing synchronisation of local environments—presumably following the Western model. This is clearly not a wholly accurate assumption, as evidenced by the complementary development or resurgence of indigenisation and particular phenomena like Africanisation, which is about cultural identity and language restoration as the face of culture conservation. Despite its lip service to diversity, differentiation, and particularities and however benevolent its motivation and intentions, internationalisation is by its very nature ultimately unable to accommodate these differences and countercurrents, especially if and where these are at odds with its central tenets (e.g. where they are manifestations of religious fundamentalism, involve nondemocratic practices). A less favourable view considers this rival trend to be a bothersome, regressive phenomenon that is facing imminent extinction.

With regard to science education, the major challenges facing internationalisation are those of accessibility and relevance. Unfortunately, Aikenhead stated that 'the "taught" science curriculum, more often than not, provides students with a stereotype image of science: socially sterile, authoritarian, non-humanistic, positivistic, and absolute truth' (Aikenhead 1996, p. 10). The traditional absolute realist view of science found in many textbooks represents a 'real science' that is outdated with few scientists endorsing it and may have never existed (Yore et al. 2004; Ziman 2000). Aikenhead characterised:

> [school] science [as] conveying an ideology that exalted Western science over all other ways of knowing… [an] ideology [that] assumed that science was purely objective, solely empirical, immaculately rational, and thus singularly truth confirming. … Scientism is scientific fundamentalism (science is the only valid way of knowing). …[Science teachers, he continued] tend to harbour a strong allegiance to values associated with scientism, for instance, science is: non-humanistic, objective, purely rational and empirical, universal, impersonal, socially sterile, and unencumbered by the vulgarity of human bias, dogma, judgments, or cultural values. … For the vast majority of students, however, enculturation into Western science is experienced as an attempt at assimilation into a foreign culture. Because students generally reject assimilation into the culture of Western science …, they tend to become alienated from Western science in spite of it being a major global influence on our lives (Aikenhead 2001, p. 2).

Haack (2003) provided a readable and understandable defence of WMS, scientism, and cynicism within reason and common sense that questions and clarifies some of these assertions. However, based on his understanding of *culture* as 'the norms, values, beliefs, expectations and conventional actions of a group' (Aikenhead 1996, p. 7) and of science as a *subculture*, Aikenhead outlined a cultural perspective on science education and culturally responsive pedagogy founded on several tenets:

1. WMS is a cultural enterprise itself, one of many subcultures of Euro-American society,
2. People live and coexist within many subcultures identified by, for example, language, ethnicity, gender, social class, occupation, religion and geographic location,

3. People move from one subculture to another, a process called "cultural border crossing";
4. People's core cultural identities may be at odds with the culture of WMS to varying degrees,
5. Science classrooms are subcultures of the school culture,
6. Most students experience a change in culture when moving from their life-worlds into the world of school science,
7. Learning science is a cross-cultural event for these students,
8. Students are more successful if they receive help negotiating their cultural border crossings, and
9. This help can come from a teacher (culture broker) who identifies the borders to be crossed, who guides students back and forth across those borders, who gets students to make sense out of cultural conflicts that might arise, and who motivates students by drawing upon the impact WMS and technology have on the students' life-worlds. (Aikenhead 2001, p. 4)

Aikenhead's context-sensitive argument, although initially attractive, rests on some rather problematic assumptions. Thus, the claim that science, science education, teaching, resources, and learning were cultural entities remains open to counter-argument. The claim that WMS is no more than one worldview among several equally valid worldviews about nature and naturally occurring events, too, remains unsupported (Yore 2008). Each of these worldviews has personal value, but they are not based on the same ontological assumptions and epistemological beliefs (NRC 1996). Surely, science is not just 'another cultural point of view' (Aikenhead 2001, p. 6); it has been a very successful human endeavour leading to positive and negative outcomes and implications. However, most people do not want their scientific beliefs to be tested by hermeneutics of religious scriptures. Nor do they want their religious beliefs to be tested by established scientific procedures. Evolution is a theory in the scientific sense—an umbrella idea that integrates other ideas and has predictive and explanatory powers; it is not merely a theory in the common lay sense—a *crazy ass* guess or a speculation among several competing, equally valid ideas (e.g. divine creation, intelligent design).

The assertion that people's core cultural identities may be at odds with the culture of WMS to varying degrees is perhaps true—in the sense that creationists' core cultural/religious identities may be at odds with science. However, many scientists and science educators report holding religious ideas and attend houses of worship, which would indicate that they maintain parallel worlds, each with specific purposes. An example might be a religious scientist standing atop a tall building and considering suicide takes time to pray, which is not for the grand architect of the universe (his god) to discontinue gravity for a few seconds after he jumps but is most likely for the grand architect to console his family and forgive his bad deeds.

Aikenhead's understanding of the aims or purposes of science education raises serious questions, when he stated that 'if the subculture of science generally *harmonises* [emphasis added] with the student's life-world culture, science instruction will tend to support the student's view of the world' (Aikenhead 1996, p. 4).

Harmonisation is the critical point here. Does this mean sensitive and respectful engagement of prior knowledge, beliefs, and experiences—a basic axiom of contemporary learning theory—or does it mean uncritical acceptance of all opinions as equally valid? '[Teachers] should teach science embedded in a social and technological milieu that has scope and force for students' worlds, worldviews, or practical experiences (respectively); and [they] need to dismantle barriers between students and science' (1996, p. 18). He later stated:

> Most students have a chance to master and *critique aspects of Western science* [emphasis added] without losing something valuable from their own cultural way of knowing. By achieving smoother border crossings between those two cultures, students are expected to become better citizens in a society enriched by cultural differences. This is an essence of cross-cultural teaching (Aikenhead 2001, p. 16).

This invites the question whether critique of Aboriginal ways of knowing, perhaps by way of critical self-reflection, is equally encouraged. If not, then how could one speak of *successful* cross-cultural teaching and learning? How does one draw a distinction between what is scientific and what is unscientific? Moreover, how does one get students to grasp the difference—if there is one? Why, according to Aikenhead, should students learn and appropriate the content of Western science at all? These are just a few questions that would need to be addressed by a compelling critique of internationalisation and its idea of the universality of science and applicability of their knowledge about nature and naturally occurring events outside of the classroom, in future studies, and for career preparation.

There is also the issue of language. In a study that builds in part on Aikenhead's ideas of cross-cultural science education and border crossing, Fakudze and Rollnick pointed out that

> African students enter the classroom with a rich heritage of traditional beliefs that, if handled sensitively and with understanding, can play an important role in enabling learning of science. Recent developments in the understanding of how students acquire this knowledge may assist in promoting this process (Fakudze and Rollnick 2008, p. 69).

They stated that

> Most learners in Southern Africa speak one language at home and are expected to study in a different language at school. The extent of separation of these two contexts is determined by whether the school is urban or rural. … [The] learning of science is further distanced from the home culture by its expression in either a second or foreign language, creating further logistical borders to be crossed (Fakudze and Rollnick 2008, p. 73).

Yore and Treagust (2006) pointed out that all learners of science face the 3-language problem (i.e. home, school, and science language), but nonspeakers of the language of instruction face much more distinct barriers and difficult transitions between these languages. Fakudze and Rollnick explored two significant possibilities: (a) using a discourse-based model to demonstrate 'how accessing either spoken or written mixed discourse may facilitate learners' comprehension of scientific discourse and allow a teacher to assist in its production' (Fakudze and Rollnick 2008, p. 76) and (b) how code switching is a useful strategy to 'facilitate the establishment of meaning by providing a linguistic and cultural bridge to understanding' (p. 78), that is, to assist border crossing in the science classroom. In so doing, they seek to augment Aikenhead's 'Cultural Border Crossing Hypothesis', which 'has not considered the issue of language' (p. 81):

> The use of language is an important aspect of border crossing and its management. … Where the two sides of the border are reinforced by a difference of language and the need for code switching, the gap can appear wider and more difficult to cross (p. 91).

Given that 'the issue of language … plays a very important role in the acquisition of science concepts' (p. 81), any account of internationalisation (or indigenisation, for that matter) that ignores this is likely to remain somewhat impoverished.

Guo (2008) examined traditional Chinese and indigenous cultural and language practices in Taiwanese science classrooms and found that the habits of mind of traditional Chinese philosophers tend to be intuitive, metaphorical, descriptive, and holistic in contrast to the rational, causal, analytical, and reductive ways of thinking that are emphasised in WMS. He also suggested that distinctive features of Chinese words and cultural beliefs might influence students' learning of science. Any teacher who believes in and uses an interactive–constructivist teaching approach (conceptual change, guided inquiry, etc.) needs to realise that nondominant language speakers will have much of their meaningful prior knowledge, experiences, and linguistic resources stored in their home language, which cannot be accessed, engaged, challenged, and applied in the dominant language of instruction. Furthermore, many of their knowledge-building language resources will be in their home language; therefore, these students need time in science classroom to share, negotiate, construct, argue, explain, and apply the prior knowledge and cognitive resources in peer groups using the same home language before whole-class deliberation in the languages of instruction and science (Yore 2012).

An additional problem with *both* internationalisation *and* indigenisation is that these approaches commit what might be called the fallacy of the collective singular. This is an essentialist fallacy that pervades reference to, say, German culture, European identity, Asian humility, the African university, the essence of Africa, and the like. The Bologna Declaration also seems to contain what Welsch has defined as 'the traditional concept of culture', where cultures are seen as separate and distinct 'islands' or closed 'spheres' (Welsch 2000, p. 330):

> The vitality and efficiency of any civilisation can be measured by the appeal that *its culture*[emphasis added] has for other countries. We need to ensure that the European higher education system acquires a world-wide degree of attraction equal to our extraordinary cultural and scientific traditions (European Commission 1999, pp. 2–3).

Botha (2010) provided a similar critique applied to Africa. In fact, neither internationalisation nor indigenisation appears to be able to do justice to the ways in which scientific content, principles, and practices—let alone culture and identity—are learned, developed, and transformed. It also remains unclear how these approaches could satisfactorily account for the worldwide attractiveness of 'the European' or 'the African' secondary and higher education system, respectively.

55.5 Multiculturality and Interculturality

Welsch's (2000) analysis of the traditional notion of culture was characterised by three pillars: social homogenisation, an ethnic foundation, and cultural delimitation. The problem, concisely, was that the depiction of cultures as separate, distinct islands or self-contained spheres was both unrealistic and normatively dangerous. It was unrealistic because it is descriptively and empirically weak, if not altogether mistaken. Throughout human history, there have been extensive transmission and dissemination (transsemination) among cultures and civilisations. Even during the eighteenth century for German philosopher Johann Gottfried Herder (to whom Welsch attributes this notion), there would have been few, if any, cultures completely untouched, uninfluenced, or not otherwise inspired by coexisting cultures. The idea of single cultures is also normatively dangerous because of its proximity to what might be called *culturism* (cultural racism, elitism, or exclusivism).

Given recognition of the significance of these problems, both empirical and normative, there have been two trends (not least in educational theory) in the latter half of the twentieth century to account for the ever-increasing transsemination and, importantly, to promote recognition, tolerance, and respect among human beings. Both multiculturality and interculturality seek to transcend the narrow confines of the traditional concept and to foster mutual understanding among cultures. Does either of these ideas provide a resolution to the impasse in the internationalisation–indigenisation debate?

Welsch (2000) argued that both concepts are problematic in that their very structure (one might say, more accurately, their grammar) still presupposes the very notion of the single cultures they purportedly repudiate. The idea of multiculturality emphasises the coexistence of different cultures within one and the same society. While this constitutes an improvement on the demand for social homogenisation, multiculturality is unable to address the resultant problems of this cultural plurality. It is not able to do so because of its conception of this multitude of cultures as individually homogenous. In fact, all it implies is the mere fact of coexistence—it says, or can say, very little about transsemination, whether descriptively or prescriptively. Welsch suggested it comes as no surprise that circumstances in the United States should have entailed some kind of justification of and increasing appeals to intercultural delimitation by theorists of multiculturality.[4]

The idea of interculturality does not appear to fare much better, for very similar reasons. It does go beyond emphasising mere coexistence of different cultures, by concerning itself with the issue of difficulty in cooperation and collaboration[5]—but it, too, conceptually presupposes the traditional conception of single, distinct cultures. Therefore, the problems it hopes to address must remain elusive since they arise because of the very presupposition that cultures are separate islands or self-contained spheres. The diagnosis of intercultural conflict is followed by

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[4] Welsch cites Amy Gutmann and Will Kymlicka, among others.

[5] See Council of the European Union (2010, p. 2).

advocacy of intercultural dialogue.[6] Yet, the basic problem remains, encapsulated in the thesis of essential separateness or distinctness of the conflicting and dialoguing cultures.[7] Thus, any of the envisaged changes would ultimately be little more than cosmetic. Nevertheless, is this thesis, which constitutes not only the traditional conception of culture but also underlies the ideas of multiculturality and interculturality, *correct*? If it were, then the problems of the coexistence and cooperation/collaboration of different cultures would remain with us—and would arguably remain unsolvable.

55.6 Transkulturalität

The central goal of this chapter—to position the IKW–WMS debate within the context of contemporary philosophical views of science and pedagogical insights into science learning and teaching—remains unsatisfied since multiculturalism and interculturalism appear to be a weak solution; one last position would be transculturalism. In Africa, *Transkulturalität*, or transculturality, presents itself as a possible response to the impasse. The central thesis is that the conception espoused in the traditional view of culture, and more or less unintentionally adopted or presupposed by the views that have succeeded it, is simply false. In other words, the depiction of cultures as islands or spheres is factually incorrect and normatively deceptive. Our cultures, Welsch (2000) suggested, no longer have the purported form of homogeneity and separateness but are, instead, characterised by mixtures and permeations. Welsch described this new structure of cultures as '*trans*cultural'—insofar as the determinants of culture now *traverse* (i.e. go *through*) cultures and *cross* their traditional boundaries and insofar as the new form *transcends* (i.e. goes *beyond*) the traditional conception (Welsch 2000, p. 335).

The understanding of transculturality so explained applies both on a macro-level, pertaining to the changed and changing configuration of present-day cultures, and on a micro-level, referring to the cultural make-up and shape of individuals. The mixtures and permeations that characterise our cultures are the result of technological advances, communication and travel, economic connectivity and dependencies, and—even more recently and importantly—of the increasing democratisation of societies. Examples of these permeations include moral and social issues and states of awareness that characterise many, if not all, allegedly different cultures: the debates about human and nonhuman rights, feminist thinking, same-sex relationships, and ecological consciousness, to mention only a few. Examples from commercial interaction (*trans*actions), sport and popular culture abound—rugby has invaded Asia, Eastern Europe, and North and South America; smart phones, hand-held technologies, and electronic gaming are ubiquitous, while hip-hop can be found in

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[6] See Aikenhead (2001, p. 4), described earlier, Problems with Internationalisation.

[7] See Welsch (2000, pp. 334–335).

Africa, Asia, Australia, and Europe. Welsch suggested that contemporary cultures are generally marked by 'hybridisation' (Welsch 2000, p. 337). Nonetheless, some critics would disagree with him when he claimed that the grounds for selectivity between one's own culture and foreign (or other) culture have all but disappeared and that

> there is little, if anything, that is strictly 'foreign' or 'other'; everything is within reach. By the same token, there is little, if anything, that can be called 'own': Authenticity has become folklore. It is ownness simulated for others, to whom the indigene himself has long come to belong (Welsch 2000, p. 337).

The transcultural (transmission between cultures) can be seen in the uptake of procedures and products among cultures and nation states. The Truth and Reconciliation process, underpinned as it was by a commitment to restorative justice, was historically and recognisably South African—even though it has been successfully applied and has transformed judicial thinking and practice, globally. Similarly, knowledge of the thirst- and appetite-suppressing qualities of the *!khoba* cactus (or *Hoodia gordonii*) originated with the San community, although the product has since been commercialised and is now available at pharmacies all over the world. Transculturality also operates on a micro-level (i.e. individual) where the vast majority of human beings are constituted in their cultural formations by a multitude of cultural origins, affiliations, and connections. 'We are cultural hybrids' (Welsch 2000, p. 339) or 'individuals in any cultural context are multiply situated/positioned' (López 1998, p. 227). We may have a particular national identity, but we may also have a multitude of cultural identities.

So, does transculturality yield a pertinent philosophical perspective on transmission of knowledge and practices, on the transformation of educational systems, or on the IKW–WMS issue? It *may*, but this verdict may require some additional conceptual clarification as well as more empirical substantiation. Welsch asserted that transculturality is itself a temporary diagnosis, which refers to a transition or, rather, a phase within a transition. It takes as its starting point the traditional idea of single cultures and maintains that this idea—whatever the appeal it may still hold for many—no longer applies, at least not to the vast majority of contemporary cultures. The concept of transculturality seeks to capture an understanding of a contemporary and future constitution of cultures that is no longer monocultural but transcultural. This does not mean that the concept of culture has become empty; according to Welsch, it makes good sense to speak of a coexistence of reference cultures and of new, transcultural nets or webs that emanate from these anchor points.

An objection that might be raised at this point may take the form of the *argument from entropy*—that the ever-increasing transsemination will itself logically lead to a kind of homogenisation, that the erstwhile individual (trans)cultural systems will become indistinguishable from one another, and that transculturality will level out in a kind of bland pan-cultural sameness, a global closed system. The argument is that not only that the idea of cultures will have been rendered redundant but the very notion of transculturality will also have ceased to apply. It would appear that Welsch himself has brought on this objection, by claiming that transculturality is itself a *temporary* diagnosis. However, further elucidation shows that the new reference cultures will themselves have transcultural configurations that are the reference point for the weaving of new transcultural webs. In addition, the different individual, social, geographical–environmental, and historical–political contexts will more than ensure that an entropic end state is highly unlikely to be bought about.

How does transculturality help address the central issue of IKW and WMS in teaching indigenous and nonindigenous students ideas about nature and naturally occurring events? Yore and Guo (2008) suggested that transcultural science instruction in Taiwan might be less conflicting (philosophy pedagogy) if indigenous technologies (e.g. animal traps, food preservation, fabrics, games, house construction, household tools, jewellery) were used to engage students and build social capital and trust before considering WMS ideas. Modern information communication technologies (smart phones, hand-held devices, etc.) and young people's ubiquitous engagement in electronic games and gaming might provide a common platform for exploring technological design and technologies. Thereby, historical technologies would serve as bridge into modern technology as design and engineering/technology practices (NRC 2012).

A prototypical example of transcultural science instruction in Taiwan illustrated the underlying principles and procedures for development of responsive and respectful approach to IKW and WMS (Lee et al. 2011). They reported on a case study of collaborative curriculum planning and teaching of a Grade 4 unit about the conception and measurement of time in an Amis (indigenous peoples of southeastern Taiwan) community school, which enrolled both indigenous and nonindigenous students. The planning involved Amis elders (knowledge keepers), the classroom teacher, and science educators identifying IKW about time events and devices and resource people that could be embedded into the prescribed unit of study and textbook coverage. Ideas about ritual celebrations, appearance of plants and animals, lunar phases, tides, and other cyclic events were embedded into the normal study of the Earth–moon–sun system; definitions of days, months, and years; and measures of minutes and hours. A reflective–responsive mechanism was used to monitor and adjust the teaching sequence and contents. Qualitative information indicated that the indigenous and nonindigenous students were engaged in the lessons and the teacher believed that the achievement of all students was much better than normal based on previous classes of students. Lee et al. stated:

> Although the current decline of Amis culture is difficult to halt, the "Measuring Time" module at least promotes student interest in learning and helps restore their cultural identity and pride. Although a cultural gap will continue to exist, we believe that students individually will adjust their innermost thoughts in ways that make sense to each student' (Lee et al. 2011, p. TBD).

Furthermore, indigenous and nonindigenous students will have a better appreciation of each other's cultures.

55.7 Conclusion: Philosophy of Education and the Role of the University

French philosophers Gilles Deleuze and Félix Guattari claimed, ‘La philosophie … est la discipline qui consiste à créer des concepts’ [Philosophy … is the discipline of creating concepts] (Deleuze and Guattari 1991, p. 10). Far more, one might argue, apart from its task being the creation of concepts (*if* it is that!), philosophy—including philosophy of education—addresses conceptual clarification and helps in determining the appropriateness or applicability of concepts, their interconnectedness, role in argumentation, etc. One of the most important functions of philosophy is arguably that of tireless critical interrogation—not only of concepts but also of premises, beliefs, values, assumptions, and commitments—and, by inquiring into their meaning and justification, not to mention their truth, to attempt to resolve some of the most fundamental ontological, epistemological, ethical, and educational questions.[8]

As Thomas Auf der Heyde (former dean of research, University of Johannesburg; 2005) has pointed out, universities clearly stand to benefit from globalisation—so, from an economic point of view, the question whether they are justified in embracing globalisation (e.g. of the knowledge economy) receives a quick and simple answer. The more interesting and difficult question is in what way, if any, their role as social observer and commentator, and their responsibility to critically reflect on the phenomenon of globalisation (Auf der Heyde 2005), can be made to complement the interest of the state, the universities’ key stakeholders, etc. If Auf der Heyde is correct in saying that ‘universities … should also be critically appraising the issues raised by [globalisation]’ (p. 41), then this is where philosophy of education arguably has its natural home. The role of philosophy consists in part in counteracting the hegemony and despotism of both homogenising (colonising) and traditional (indigenising) authority.

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[8] See McLaughlin (2000, pp. 444 & 448), Wimmer (2000, pp. 413–414).

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Chapter 56
Science, Religion, and Naturalism: Metaphysical and Methodological Incompatibilities

Martin Mahner

56.1 Introduction

In many countries, children receive both science education and religious education.[1] "Religious education" is here understood as an education under denominational auspices, however liberal. That is, students are not taught some unbiased comparative, historical, cultural, and social aspects of religion, but are expected to accept and internalize the doctrines of a particular religious belief system, usually the one their parents are affiliated to.[2] From a nonreligious perspective, this situation is unfortunate as it appears that an education emphasizing the need for empirical tests and evidence is incompatible with an education that allows for, or even encourages, the acceptance of factual beliefs without or even contrary to evidence. In other words, learning to accept statements only if there is sufficient evidence for them and learning to accept claims on sheer faith appear to be antagonistic educational goals (Mahner and Bunge 1996a; Martin 1997).

Evidently, this concern rests on the assumption that science and religion are mutually incompatible, whereby "incompatible" means that one cannot rationally accept both a scientific and a religious world view. Though common among (consistent) naturalists and secular humanists,[3] this view is of course contested by many

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[1] This contribution uses material published earlier in the journal *Science & Education*, namely, from Mahner and Bunge (1996a, b) and Mahner (2012).

[2] Of course, there are approaches to teach religion in a very general sense of "spirituality," whatever that exactly means (see, e.g., Stolberg and Teece 2011). Even so the presupposition is that this spirituality comprises more than what can be obtained in a comprehensive scientific worldview.

[3] See, e.g., Clements (1990), Dawkins (2006), Dennett (2007), Edis (2007, 2008, 2009), Kanitscheider (1996), Kitcher (2004), Kurtz (2003), Mahner and Bunge (1996a, b), Martin (1997), Provine (2008), Rachels (1991), Smart (1967), Stenger (2007, 2011), and Suchting (1994).

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religionists and even some naturalistically inclined scientists and philosophers.[4] Therefore, it will be necessary to defend it. If we succeed in showing that science and religion are incompatible, it is a mere corollary that science and religious education are also incompatible.

Any argument for either the compatibility or incompatibility of science should work with a reasonably clear definition of both *science* and *religion*. However, the very existence of such definitions has been contested for a long time (see, e.g., Glennan 2009). There have been arguments to the effect that there is no reasonable demarcation between science and nonscience, in particular pseudoscience (Laudan 1983), and that, similarly, religion is so diversified that any attempt to formulate a definition that covers all religions is futile (Platvoet and Molendijk 1999). As this is not the place to review these arguments,[5] it will be helpful to narrow down what we take science and religion to be, so that we can focus on those aspects that may or may not be compatible. Before we get to this point, however, it will suffice to work with the undefined everyday usages of "science" and "religion." So we start with the question of how to avoid conflict between religion and science.

56.2 How to Avoid Conflict Between Religion and Science

Claims, theories, or world views may be in mutual conflict only if there is an at least partial overlap in their subject matter. Indeed, traditionally religions have offered general cosmologies (or metaphysics) helping to explain the major features of the world, in particular the place of humans and their relationship to the various supernatural entities allegedly populating the world alongside humans. After all, "[a]ll religions do share a feature: ostensible communication with humanlike, yet nonhuman, beings through some form of symbolic action" (Guthrie 1995, p. 197) – and this requires some factual background assumptions. While science has emerged from such a religious cosmology, it has now superseded the latter, it has significantly changed its metaphysical framework, and it has taken over the explanatory function of the old cosmologies. It appears therefore that, concerning matters of fact, religion has ceded this explanatory role to science, focusing now on other tasks. And it appears as if this concession has removed any former conflicts. While we shall see later on that this appearance is deceptive, let us first take a look at the attempts at reconceptualizing either religion or science to prevent them from being in conflict.

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[4] See, e.g., Alston (2004), Barbour (2000), Clayton and Simpson (2008), Drees (1996), Gould (1999), Harrison (2010), Haught (1995), Peacocke (1993), Polkinghorne (1987), Rolston (1987), Ruse (2001a, 2011), Stenmark (2010), and Wentzel van Huyssteen (1998).

[5] For critiques of Laudan's view, see Mahner (2013) and Pigliucci (2013). For a comparison of concepts of religion, see Guthrie (1995). As for the demarcation of science in general, see Mahner (2007) and Thagard (2011).

56.2.1 Science and Religion Deal with Different Aspects of the World or Even with Different Realities

There are several ways to render science and religion independent so that they cannot be in conflict. One way is ontological. It splits the world into two radically different parts: a material world (nature) and a transcendent world (supernature). Whereas nature is studied by science, supernature is studied by religion.[6] A historically important example of this approach is deism, which allowed scientists to study the natural world without resorting to supernatural interventions (apart from the initial act of divine creation). However, conflict with science can only be avoided if these two worlds are causally independent: if there are causal interactions, we sooner or later face conflicting explanations. Yet if such a supernature is causally independent of the natural world, there can be no evidence for its existence so that it remains merely a conceptual possibility, moreover, one without any explanatory function as its existence or nonexistence would make no difference to our world. Such a radical split then is not very attractive to most religious believers, who usually long for a connection between themselves and the divine.

A second ontological possibility is to assume that supernatural agents are not agents in the familiar sense, but only "underlying" causes. While natural causes are (merely) "secondary causes" studied by science, God works as the "primary cause" behind the scenes. Indeed, according to some authors, God has been rather busy pulling the strings behind quantum physics and evolution, for example (Freddoso 1991; Barbour 2000; Plantinga 2011). The concepts of agency and cause involved here are best understood from the viewpoint of Scholastic metaphysics, which, though long superseded in science, is still going strong in Catholic philosophy. From a naturalist perspective, the involvement of supernatural agents "behind" natural causes is an unparsimonious and hence superfluous add-on to natural causes.[7] Assuming sustaining supernatural causes behind the web of natural causes does avoid conflict at the superficial level of the daily business of science and religion, but it does not avoid conflict at the deeper metaphysical level.

A third way of keeping science and religion separate is methodological and referential. Science and religion have different tasks, and they study different objects, or different properties or aspects of the world. For example, Rolston (1987) claims that religion is concerned with morality and meaning (not in the semantic sense of course, but in the sense of "purpose"), not material facts.[8] Following this

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[6] It may be argued that attempts to split the world into two or more "worlds" are incoherent because, by definition, the world is everything that exists (Worrall 2004). However, if our metaphysics requires that not any old collection of causally unconnected things is itself a material thing and hence a real entity, worlds are real things (or, more precisely, systems) only inasmuch as their parts are causally connected, however weakly. Two causally unconnected universes would then be two different things, and there would be no supersystem of which they would be physical parts.

[7] For the metaphysical and epistemological problems of the idea of divine intervention, see Fales (2010).

[8] For an analysis of the various meanings of "meaning" in this context, see Martin (2002). For a critique of related noncognitive concepts of religion, see Philipse (2012).

idea, the evolutionary biologist Stephen J. Gould devoted an entire book to the "nonoverlapping magisteria" (NOMA) of science and religion (Gould 1999). Of course, if two areas have different referents, goals, and methods, they can hardly be in conflict. Dancing tango and doing science are not in conflict because they are quite different pursuits. Moreover, the NOMA approach allows for the claim that science and religion are not just compatible, but even complementary: morality and the search for purpose belong to human life just as the factual study of the world.[9]

The average religious believer, however, has to pay a high price for NOMA, because the concept of religion has to be redefined in a major way; so much so that no ordinary believer may recognize it afterwards.[10] For example, Gould considers as religious "all moral discourse on principles that might activate the ideal of universal fellowship among people" (Gould 1999, p. 62). This definition is so wide that it even applies to secular ethical discourse. So if an atheist engages in such discourse, he would be religious. While being too wide on the one hand, this definition is too narrow on the other, because it presupposes that religion has no factual content. For example, whatever people have said about the soul and the afterlife, or about the existence and properties of gods or cosmic forces, is illegitimate because it involves factual, not ethical, discourse. As a consequence, most traditional religious "truths" are excluded from the legitimate business of religion. Worse, without some factual assumptions about gods (for instance, god's will) or the order of creation (natural law doctrine) or the karma, moral values and norms cannot even be justified in a religious world view (Nowell-Smith 1967). As McCauley states:

> Religions certainly do try to make sense of our lives and of the world in which we find ourselves. The problem, though, is that that process of making sense of things inevitably involves appeals to explanations about the origins, the makeup, and the behavior of things generally and about our origins, makeup, and behavior in particular. (McCauley 2011, p. 229)

Last but not least, it can be argued that ethics cannot even be based on religion (see, e.g., Rachels 1995; Martin 2002). Thus, the identification of religion with ethics fails and hence also the "different domains" approach.

56.2.2 Religion Is Not Necessarily Bound to Supernaturalism

If science is tied to naturalism, whereas religion is based on supernaturalism, as is widely held, there is ample room for conflict at both the metaphysical level and the level of scientific explanation. But is religion really tied to a supernaturalist metaphysics? According to quite a number of scientists and philosophers, it is not. Indeed, Auguste Comte, John Dewey, Henry Wieman, Julian Huxley, Charles

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[9] In science education, Sinatra and Nadelson (2011) follow this approach by postulating different epistemologies for science and religion, that is, "epistemologies that have different roles and explain different aspects of the human condition" (p. 175). Obviously, and sadly, this is an instance of epistemological relativism.

[10] See McCauley (2011), Orr (1999), and Worrall (2004).

Hardwick, and others have argued for religious naturalism.[11] Thus, "God" is redefined as the unity of our ideals, or as a cosmic process unfolding for the benefit of humans, or as the creative exchange among humans, etc. Often feelings of awe towards nature or the universe are regarded as religious feelings or as a feeling of the "sacred." For example, Einstein (1999) believed that the scientist's religiosity lies in "the amazement at the harmony of natural law."

Whether pantheism is a form of religious naturalism remains unclear. In an everyday understanding according to which the world is God, pantheism does appear to be a naturalist conception. In this sense, however, Schopenhauer's criticism applies: "to call the world 'God' is not to explain it; it is only to enrich our language with a superfluous synonym for the word 'world'" (Schopenhauer 1951, p. 40).[12] Levine (2011) rejects Schopenhauer's criticism for resting on a misunderstanding of what the pantheistic "divine unity" of the world means. However, Levine's own characterization of "unity" is fuzzy to the point of being incomprehensible, and he regards "divine" simply as experiential: whatever someone experiences as numinous is divine. Thus, the divine is turned into a subjective category.[13]

With the exception of traditional pantheism, it appears that the common motif of such non-supernaturalist approaches is to redefine "religion" in terms of either feelings or experiences, leaving no room for any factual content of religion. As Barbour (2000, p. 159) rightly remarks, religious naturalism thus simply conflicts with "most of the heritage of religious traditions."

56.2.3 Defining Religion in a Merely Functional Way

Psychologists and sociologists usually refrain from defining "religion" in a substantive way, that is, with regard to its content. Instead, they define it in terms of the functions religious beliefs, practices, and institutions have in human life and society

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[11] See, e.g., Alston (1967), Drees (1996, 2008), and Hardwick (2003).

[12] To the consistent naturalist, the attempt to naturalize religion reduces to a game of words:

> The bogus procedure is this: When there is something that clearly does not exist, but one wishes that it did exist and wants to be able to say that it does exist, then choose something real that is similar in some respects and give it the name of the nonexistent entity. Voilà! You have now proved the existence of something that doesn't exist. Suppose one wants to prove that God exists. Find something awe-inspiring, or powerful, or infinite, or fundamental …. and call it "God". Now God exists, and the various practices with respect to that God are "religious". Unfortunately, in reality, all you've done is play with words and, thereby, pull off a shabby, unconvincing trick. (Pasquarello 2002, p. 51)

This applies not only to religious naturalism but also to the various hermeneutic approaches in modern theology, such as Paul Tillich's definition of God as "ultimate concern" (for a criticism of hermeneutic theology, see Chap. 5 in Albert 1985).

[13] Peacocke's (1993) panentheism does not seem to be a consistent naturalism, as it makes God only partly natural, so I shall not discuss his view here.

(see, e.g., Yinger 1970). That religious beliefs and practices have evolved along with humankind and that they have various functions for individuals and groups is of course nothing but a scientific description and explanation of religion.[14] It is exactly these functions that remain once the cognitive content of religion is removed for being illusory. Obviously, a naturalist, scientific view of religion cannot be in conflict with science. Yet again, the problem remains that such characterizations do not match the self-conceptions of most religions.[15]

56.2.4 The Argument from Religious Scientists

Another psychological and sociological argument to consider is the claim that science and religion cannot be in conflict because there have been many religious scientists. Indeed, quite naturally there is no shortage of historical examples, which are often used to reject the historical conflict view (see, e.g., Russell 2002). And even today the number of religious scientists is high.[16] Interestingly, average scientists tend to be more religious than elite scientists (Gross and Simmons 2009). According to the latest study of Ecklund (2010), about 64 % of elite US scientists are atheists or agnostics.

The argument from religious scientists, however, is a weak one at best. At worst, it is an *argumentum ad populum*. It would come as no surprise that a large number of people can be mistaken about something. And as we know from psychology, many people hold inconsistent beliefs. This applies also to scientists. For example, it is quite telling that most religious scientists have not used religious concepts in their scientific work (Mahner and Bunge 1996b). There are no variables referring to supernatural entities or processes in scientific theories. If someone believes in the reality of the supernatural, it is inconsistent to not make use of religious entities and methods in science. Rather, we should expect religious scientists to defend a theistic science, as Ratzsch (1996) and Plantinga (2001) consistently (though of course unsuccessfully) do. But this is rarely the case. Therefore, pace Ratzsch (2004) and others, it is not implausible to suspect the world views of religious scientists to be inconsistent.

So the problem of whether science and religion are compatible or not is not a matter of psychology and sociology but of philosophy, more precisely, of metaphysics, epistemology, and methodology. If there is no conflict at this level, then the world view of religious scientists may be consistent; otherwise, it is not.

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[14] See Boyer (2001), Dennett (2007), and Guthrie (1995).

[15] Further criticism of religious functionalism in Guthrie (1995).

[16] See, e.g., Ecklund (2010), Gross and Simmons (2009), Larson and Witham (1998), and Margenau and Varghese (1992).

56.2.5 Religious Discourse Is Nonsense

According to neopositivism, metaphysical sentences including religious ones are semantically nonsensical because they are not verifiable (Ayer 1990). If religious discourse is nonsense, it can be neither compatible nor incompatible with scientific discourse. So there is no conflict with science. As a consequence, however, atheist discourse is nonsensic too: if "God exists" is nonsense, its negation "God does not exist" is also nonsense.

It is rather obvious that the neopositivist answer is not a good option for religious believers. After all, they believe that they make meaningful statements about nature or supernature or both. Indeed, the neopositivist meaning criterion of verifiability has long been abandoned: in order to verify or falsify a statement, it must be semantically meaningful in the first place, not the other way round. So we cannot keep religion away by declaring it nonsense *tout court*. However, in particular academic theology does have meaning problems, as it often resorts to an irrationalist, fuzzy discourse that helps to immunize theology from factual criticism (Albert 1985; Bartley 1984). And as we shall see later, it is not at all clear what the very term "God" exactly means.

56.2.6 Distorting Science

Removing the cognitive content of religion is not the only way to avoid conflict between science and religion. There are also attempts to remove all truth claims from science by adopting antirealist views of science, such as instrumentalism or relativism. If scientific theories are not attempts at approximating truth by stating something about how the world really is, but only more or less useful tools for systematizing or predicting empirical statements, or if scientific theories are nothing but yet another way at looking at the world, on the same par as any other, even mythical way, then science may of course peacefully coexist with religion (Byl 1985; Stenmark 2010). A less radical view is constructive empiricism, which replaces truth by empirical adequacy, but it too is a view that castrates science. Given the fact that both instrumentalism and constructive empiricism are still popular in the philosophy of science, at least much more so than relativism, it may appear bold to charge them with distorting science, but this is not the place to defend this view.[17]

56.2.7 Conclusion

As we have seen, there are many ways to construe "religion." Some of them would indeed be compatible with science. But as we have also seen, the believer has to pay a high price if he accepts them. Religious entities are either rendered causally

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[17] More on this in Vollmer (1990), Psillos (1999, 2003), Worrall (2004), and Ladyman (2012).

inefficacious and hence irrelevant, or religion is emptied of any factual content so that it can no longer make any (objective) truth claims. Notwithstanding the attempts of modern theology at immunizing religion from criticism by obfuscating and subjectifying its concepts (Albert 1985), the vast majority of believers of all ages has believed that their religion does make some true factual statements about the world, in particular about humans and their relation to the divine or at least to certain spiritual entities (McCauley 2011). That is, real life religions have always included a cosmology.[18] The following characterization reflects this situation. Accordingly, religion can be seen as

> …the belief in numinous personal or impersonal entities - gods, spirits, demons, angels, or divine powers - which have certain causal powers, and which therefore are relevant to human fate and salvation, as well as […] an associated practice of the believers, which is adequate to make allowance for the powers of these entities and to influence them for the benefit of the believers' salvation, that is, a cult characterized by a salvation technology. (Albert 2000, p. 142, my free translation)

Both religion and science thus have an overlap in that they are epistemic enterprises. Both search for truth, partly in the same, partly in different domains. We can therefore construe both as epistemic fields.

56.3 Science and Religion as Epistemic Fields

In the following, science and religion are compared by means of a list of criteria that helps to define epistemic fields.[19] By "science" I mean factual science as opposed to formal science like logics and mathematics. Now, factual science is often called "empirical science." However, "empirical" refers to the methods of science, not to the concrete facts it studies. Science studies concrete facts (material things having certain properties and the processes they undergo) by both theoretical and empirical means. So by "fact," I do not mean *statements* about concrete facts but the referents of such factual statements. I shall ignore the question of whether there are formal or abstract facts as these do not exist in the same way as concrete facts. The following questions yield some of the criteria that help to define an epistemic field:

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[18] This is echoed by Plantinga who has the gall to call naturalism a quasi-religion because it fulfills this world view aspect: "It offers a way of interpreting ourselves to ourselves, a way of understanding our origin and significance at the deep level of religion. It tells us where we come from, what our prospects are, what our place in the universe is, whether there is life after death, and the like. We could therefore say that it is a 'quasi-religion'" (Dennett and Plantinga 2011, p. 16f., see also Plantinga 2011). Needless to say, it is disingenuous to call a world view that has overcome religion a quasi-religion. A similar theological ploy is to compare the philosophical underpinnings of science to religious faith.

[19] Modifiyng earlier analyses by Bunge (1983), Bunge and Mahner (2004), Mahner (2007), and Mahner and Bunge (1996a).

1. Which objects does it refer to? What is the domain of facts it is concerned with?
2. What is its fund of knowledge?
3. Which background knowledge does it use in the study of its domain?
4. What are the aims of the given field?
5. Which methods does it work with?
6. Which are the philosophical background assumptions presupposed in its work? That is, what are its metaphysical, methodological, axiological, and moral foundations? Finally, which general attitude or mind-set is considered to be exemplary for those who work in the given field?

56.3.1 Science

1. The domain of factual science comprises everything existent, i.e., the whole world. Although there are certainly things that are de facto beyond scientific investigation for lack of information, there is nothing natural that could not be de jure studied scientifically. As a matter of principle, the domain of science also includes, for instance, the how and why of subjective feelings and emotions in general, as well as the origins and functions of morality and religion – fields of inquiry that are sometimes believed to be beyond scientific understanding.
2. The fund of scientific knowledge is a body of factual knowledge, in particular law statements, which grows along with research. (More on laws in Sect. 56.4.1.)
3. The background of a specific scientific field is the collection of up-to-date well-confirmed knowledge (data, hypotheses, theories) borrowed from neighboring fields. Each scientific discipline connects thus to other scientific fields. Science consists of a network of subfields or disciplines, aiming at a consilient description of the world.
4. The aims of a basic science are purely cognitive. They include, for example, the discovery of the laws of its referents, the explanation of the facts it studies, the systematization of its knowledge base (e.g., by constructing general theories), and the refinement of its methods. By contrast, the aims of technology are practical: it is concerned with design and application.
5. The *methodics* of a scientific field is the collection of its specific and general methods, where specific methods are often called "techniques." (The term "methodology" is reserved here for normative epistemology.) For example, scanning electron microscopy is a specific method, whereas the scientific method is the most general method of the sciences. Specific methods must be scrutable and objective, and we must be able to explain, at least roughly, how they work. The scientific method in general may be conceived of as consisting of the following ordered sequence of cognitive operations: Identify a problem–search for information, methods, instruments–try to solve the problem with the help of those means; if necessary, invent new means, produce new data, or design new experiments–derive the consequences of your solution (e.g., predictions)–check

the solution (e.g., try to replicate your findings by alternative means)–correct the solution if necessary in repeating the cycle–examine the impact of the solution upon the body of background knowledge and state some of the new problems it gives rise to. The structure of any scientific paper roughly reflects these steps and is thus an instance of the scientific method. Of course, there is no single specific method that could be applied to each particular case of research.

6. The philosophical background assumptions of science comprise a naturalist ontology (or metaphysics), a realist epistemology, and a system of values that is particularly characterized by the ethos of the free search for truth.[20] The value system of science includes such logical values as exactness, systemicity, and logical consistency; semantical values such as meaning definiteness (hence clarity) and maximal truth (or adequacy of ideas to facts); methodological values such as testability and the possibility of scrutinizing and justifying the very methods employed to put ideas to the test; and, finally, attitudinal and moral values such as critical thinking, open-mindedness (but not blank-mindedness), veracity, giving credit where credit is due, and more.

These philosophical assumptions are by no means generally accepted in the philosophy of science, so each of them would need further justification. Since there is no room to justify all of them here, the focus will be on the two most important aspects: the metaphysics and methodologies of science and religion. But let us take a closer look at religion first.

56.3.2 Religion

1. In addition to all religiously relevant parts of nature and society, the domain of religion comprises also supernature. Of particular interest are of course the relations of natural things (especially humans) to supernatural entities, and vice versa.
2. The fund of knowledge is a fixed or at most slowly changing collection of (mostly untestable) doctrines and beliefs, whether conveyed by means of an oral tradition or through sacred scriptures. Whatever change in religious beliefs may appear to take place is not due to research and hence newly discovered facts but is almost entirely a result of either (a) a change in the exegesis and interpretation of traditional doctrines, which, if taken literally, often are unpalatable to modern people, or (b) squabbles or even wars between rival factions in the same religious community. Hence, any substantial changes in the belief system are due to authority or external influence, not research. If genuine research takes place, such as historical investigation, this research is not accomplished by religious but scientific means even if undertaken by theologians. Accordingly, it has to be regarded as an external influence.

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[20] "Ontology" is used synonymously with "metaphysics" in this paper.

3. The factual background of religion contains at best ordinary knowledge, not scientific knowledge. This is just because most religions are older than science. Some scientific knowledge may be compatible with religious doctrines up to a certain point, and some theologians may make use of scientific knowledge in certain arguments, but in the end this should not be necessary for the (alleged) truth of any religious doctrine.
4. The aims of religion are foremost practical. Moreover, they are ultimately, though mostly tacitly, a matter of self-interest in that they consist in attaining personal advantage such as salvation or eternal life (individual or cosmic). Religions are salvation technologies after all. To obey and worship the divine, or to live a virtuous life, though the explicit goal of the religious person, is, in the end, only a means to attain the blessings expected from the supernatural. All religion is ultimately anthropocentric.
5. The methodics of religion is a collection of practices, such as prayer, incantation, fasting, meditation, and other rituals that are supposed to connect human beings to the supernatural. As far as a cognitive aim is pursued, the religious person may make use of intuition, contemplation, meditation, or revelation. There is neither use for the scientific method in general nor use for specific scientific techniques.
6. The philosophical background assumptions of religion consist of a supernaturalist metaphysics, which is a collection of doctrines about the supernatural and our relations to it. Supernatural entities may be impersonal forces such as karma or more or less anthropomorphic "persons" such as gods. The epistemology of religion is usually a realist one, though religion may be consistent with any epistemology. The value system of religion seems to have only one item in common with science: the quest for truth. However, whereas the truth looked for by religionists is absolute or ultimate, scientific truth is partial or approximate. Neither exactness nor logical consistency and neither clarity nor testability are strong in religion. Moreover, it can be argued that many religious beliefs can only be upheld by disregarding such values. Otherwise, it would not be possible to cherish the mysterious or to confess *credo quia absurdum*. A religious value that is alien to science is (blind) faith, which allows the religionist to always retreat to commitment or fideism if pressed by rational analysis (Bartley 1984). Finally, religion contains an ethos of acceptance and defense of unquestionable doctrines, i.e., dogmas. As for the latter, witness Augustine's dictum, "Greater is the authority of Scripture than all the powers of the human mind," or Paul's injunction "Beware lest anyone cheat you through philosophy and empty deceit, according to the tradition of men, according to the basic principles of the world, and not according to Christ" (Col. 2: 8).

56.3.3 Conclusion

The above listed several commonalities and differences between science and religion, among them some obvious incompatibilities. Both science and religion aim at gaining knowledge about the world. Both operate from a realist perspective, and both are truth seekers. While, today, most of the world is left to science to study and explain, there is an area of overlap the closer we get to the description and explanation of the place of humans in the world. The differences concern the nonnaturalist metaphysics of religion as well as, among others, the methodological status of evidence versus faith and the role of authority versus the free search for truth. And these differences will turn out to be the major incompatibilities.

56.4 The Metaphysics of Science and Religion

Modern science emerged from a mixture of prescience, philosophy, and religion. These areas were strongly intertwined during Scholasticism, but developed apart from the early sixteenth century on (Schrader 2000; Matthews 2009). The emancipation of science from theology is thus one of the characteristic features of its development. Mainstream philosophy also emancipated itself from theology, although even today philosophy in general is still so diverse that it ranges from materialism to quasi-religious thinking and even obscurantism. Even authors who come to a rather conciliatory conclusion concerning the historical relationship between science and religion admit that the main area of conflict concerns metaphysics: "The famous episodes of conflict between science and religion are not strictly conflicts between science and religion. Rather, they are instances of a more general conflict that arises within the process of changing metaphysical frameworks" (Schrader 2000, p. 400). For example, science superseded Scholastic metaphysics, in particular the teleology inherent in its Aristotelian foundation. It also abandoned the intentional teleology of the long-respectable argument to design. Indeed, the result is that, today, the metaphysics of science is consistently naturalist, which is incompatible with any supernaturalist metaphysics, however minimally furnished it may be.

This raises the question of whether the naturalism of science is just the result of a contingent historical development or whether this historical development has just brought forward what had applied all along: naturalism as a metaphysical condition of science. This latter thesis will be defended here.

Now, metaphysical conditions or presuppositions are not exactly popular in contemporary analytic philosophy because they smack of Kantianism. Kantian apriorism is the very antithesis of the aposteriorist approach of epistemological and methodological naturalism, which is widespread in contemporary analytic philosophy. However, metaphysical presuppositions need not be apriorist in the Kantian sense. But what is meant then by "condition" or "presupposition"?

A presupposition is often understood in the sense of a statement that is entailed by a set of premises or in the sense of a necessary condition implied by some antecedent statement. Is metaphysical naturalism entailed by science in one of these senses? From a formal point of view, it is not. It is not part of a deductive argument in the sense that if we collected all the statements or theories of science and used them as premises, then metaphysical naturalism would logically follow. After all, scientific theories do not explicitly talk about anything metaphysical such as the presence or absence of supernatural entities: they simply refer to natural entities and processes only. Therefore, naturalism rather is a tacit metaphysical *supposition* of science, an ontological *postulate*. It is part of a metascientific framework or, if preferred, of the metaparadigm of science that guides the construction and evaluation of theories and that helps to explain why science works and succeeds in studying and explaining the world. As such, it is the best framework available yet, justified by its very success and its unifying and heuristic power.

56.4.1 The Metaphysical Presuppositions of Scientific Research

> …what Kant and Hume show, I think, is that limiting oneself to seeking natural causes for natural effects is not […] a metaphysical principle with no inherent grounding in science but rather a disciplinary condition of doing science, the only way to get the particular kinds of answers that science seeks within the terms of the evidentiary warrants it demands. (Loesberg 2007, p. 96f.)

A popular view among scientists maintains that science need not bother with philosophy, let alone metaphysics, at all; scientists should just apply and follow the scientific method or, if preferred, the collection of scientific methods. Somewhat more sophisticatedly, if science is ultimately about finding the truth, all that counts is evidence. Whether it confirms the natural or points to the supernatural, we should follow the evidence wherever it leads (Fishman 2009; Monton 2009). This antimetaphysical stance is importantly wrong because it rests on the assumption that both scientific methods and the evidence they produce are free of metaphysical presuppositions.

To show that there is quite a number of metaphysical postulates of science (Bunge 1983), we take a look at the three (overlapping) general empirical methods in science by means of which we gain data, which, in turn, may function as evidence: observation, measurement, and experiment. The question is whether these methods can work in a metaphysical vacuum, or whether their successful application rests upon certain metaphysical assumptions. In other words, could these methods work successfully in just any world, or can they work only in a world with a particular nature? A simple experiment chosen from a high school biology textbook will function as an example (Fig. 56.1, following Mahner 2007).

Let us focus here on the question of how much metaphysics is hidden in this simple experiment, addressing possible objections mostly in footnotes so as not to interrupt the exposition.

First, we assume that this experiment involves real entities in a real world, not just objects existing in our mind. That is, we work on the basis of ontological realism, which helps to explain not only the success but in particular the failure of scientific theories.[21]

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[21] A very general ontological realism is probably the least controversial metaphysical presupposition of science (Bunge 1983, 2006; Alters 1997; Gauch 2009; Ladyman 2012), although there is an ongoing realism/antirealism debate in philosophy. However, this debate concerns mostly epistemological

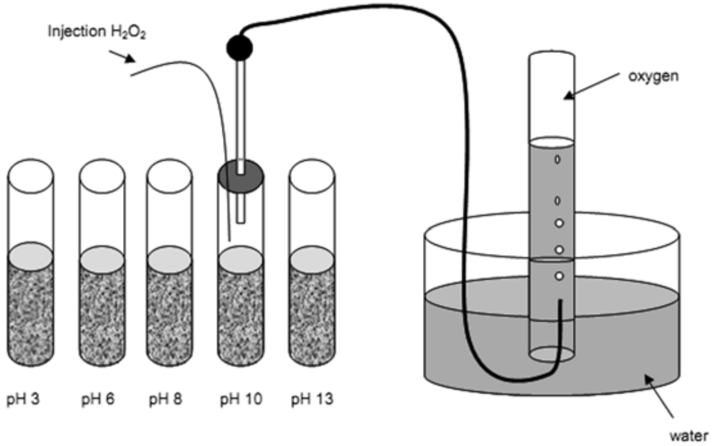

Fig. 56.1 By determining the pH optimum of the enzyme catalase, this experiment is used to demonstrate that the functioning of enzymes is pH dependent. The experimental setup is as follows. Five test tubes are halfway filled with water. We add a piece of yeast to each of them. By adding different amounts of hydrochloric acid (HCl) or caustic soda (NaOH), we arrange for a different acidity or alkalinity, respectively, in each tube, say, pH 3, pH 6, pH 8, pH 10, and pH 13. The yeast cells contain the enzyme catalase, which enables them to break down hydrogen peroxide into water and oxygen (i.e., $2\ H_2O_2 \rightarrow 2\ H_2O + O_2$). We inject a certain amount of hydrogen peroxide solution into the test tubes (e.g., by means of a syringe). Each time, we close the tube and measure the amount of gas produced after 2 min by collecting it in a measuring tube, which is connected to the given test tube by a thin rubber hose. We do not need to specify the precise amounts and conditions here, because the basic setup of this experiment will be clear anyway (from Mahner 2007; redrawn and modified from Knodel 1985, p. 39). The result of this experiment: the oxygen production is highest at pH 8 (in fact, at pH 8.5, which can only be discerned by refining the experiment)

Now that we are talking real test tubes with real yeast and real chemicals, we may ask why an experiment like this is found in a textbook. Obviously, we assume that we can repeat this experiment as many times as we see fit, and that we will obtain (roughly) the same results, provided we do not make any mistakes. The gas produced is always oxygen, neither nitrogen nor carbon dioxide. The test tubes remain test tubes, and do not spontaneously transform into chewing gum or thin air. It appears then that things and their properties remain the same under the same conditions. Certain properties of things seem to be constantly connected, so that they change together: they are covariant. In other words, certain properties of things are lawfully related.

Of course, ordinary experience already indicates that the world is lawful, but the thesis of a lawful world is not a piece of empirical knowledge: it is a necessary condition of cognition. Without things behaving regularly due to their lawful properties, no organism would be able to learn much about the world. Note that

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problems regarding the justification of more detailed realistic claims such as the status of unobservable entities and the truth of scientific theories. Thus, someone who rejects more specific forms of realism, such as scientific realism, usually is still an ontological realist. I shall not defend ontological realism in more detail here (for such a defense, see, e.g., Vollmer 1990), because both ontological naturalists and supernaturalists share a basic realist outlook anyway.

what I am referring to here are laws in an ontological sense of lawfully related properties, not general law statements as conceptual representations of such ontic laws (Bunge 1983, 2006; Ellis 2002). This must be emphasized because the view that laws of nature are nothing but universal statements is still popular.[22]

Imagine next that we fail to obtain oxygen in our measuring tube. In this case we would look for mistakes in the setup, like a leakage in the rubber tube. We would check whether the yeast is still alive, whether we have correctly set the pH value of the water, or whether the substance we add is really a hydrogen peroxide solution. No scientist would seriously entertain the idea that somewhere in the experimental setup the gas has literally dissolved into nothing. Conversely, no scientist would assume that we can produce gas out of nothing. There is simply no point in doing experiments and "wiggling parameters" if things simply could pop out of or into nothing. Let's call this the ex-nihilo-nihil-fit principle.[23]

What initiates the production of oxygen? Oxygen does not originate spontaneously: it starts to emerge only after we add some hydrogen peroxide solution. Thus, by meddling with certain parts of the setup, we can produce a certain effect: we can

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[22] I submit that the mainstream view of laws in the philosophy of science is inadequate. Science calls for a (neo-)essentialist view of laws, according to which "the laws of nature are immanent in the things that exist in nature, rather than imposed on them from without. Thus, [. . .] things behave as they do, not because they are forced or constrained by God, or even by the laws of nature, but, rather, because of the intrinsic causal powers, capacities and propensities of their basic constituents and how they are arranged" (Ellis 2002, p. 1). Thus

> not even an omnipotent God could change the laws of nature without changing the things on which they are supposed to act. Therefore, the idea that the laws of physics are contingent, and superimposed on intrinsically passive things that have identities that are independent of the laws of their behavior, is one that lies very uneasily with modern science. (Ellis 2002, p. 5)

The lawful behavior of things neither entails that we can always represent them as law statements nor that every scientific explanation is a subsumption under some law. For example, due to the enormous variation of organisms, many biologists believe that there are no laws (= law statements) in biology. But this does not entail that organisms do not behave lawfully: it is just that it often makes not much sense to try to find general, let alone universal, law statements because their reference class is rather small, holding only for some subspecies, variety, or even smaller units, for example, that is, only for those organisms sharing the same lawful properties (more on laws in biology in Mahner & Bunge 1997, Ellis 2002). Finally, even some cases of randomness are lawful because they are based on stochastic propensities such as in quantum physics. That is, there are probabilistic laws. For the neo-essentialist approach to laws adopted here, see Bunge (1977), Mahner and Bunge (1997), Bunge and Mahner (2004), and Ellis (2002).

[23] Note that "nothing" really means "nothing," not some form of radiation or some other massless form of matter. For example, what is called particle annihilation is just a transformation of a particle with mass into one or more massless particles, that is, into some form of radiation. However, it seems that the ex-nihilo-nihil-fit principle is being challenged by cosmologists, who keep entertaining the idea that the universe originated from nothing (see, e.g., Stenger 2011). In particular, according to multiverse cosmology, some primordial "nothing" keeps randomly popping out universes. But since this "nothing" has at least one property, namely, the propensity to pop out universes, it doesn't seem to be a genuine nothing which should have no properties at all and hence be unable to change.

(causally) interact with the setup. Moreover, the steps in this chain of events are ordered: their sequence is not arbitrary. That is, we must assume that causation is for real and hence an ontological category, as well as that there is a principle of antecedence: causes precede their effects in time, so that the present is determined causally or stochastically by the past, but not conversely. In other words, we need to assume not only that the experimental setup (or the world in general) is real but also that we can interact with it and that our actions can trigger orderly chains of events. Otherwise, no deliberate effect could be produced, variables could not be controlled for, etc.

If the results of our empirical methods are expected to be the results of real processes in a real world, we must rule out the possibility that the experimental setup can be causally influenced in a *direct* way solely by our thoughts or wishes (or more precisely our thinking and wishing), that is, without the interposition of motoric actions by our bodies (Broad 1949). Indeed, if the world were permeated by causally efficacious mental forces, we would have no reason to trust the reading of any measuring instrument or the results of any experiment. In other words, the data obtained through observation, measurement, or experiment could not function as evidence if they were literally the telepathic or psychokinetic product of wishful thinking. Worse, we could not even trust our own perceptions and conceptions, as they could be the result of telepathic manipulation. We may call the assumption that no such mental forces exist the "no-psi principle" (Bunge 1983, p. 106).[24] This principle must hold not only for humans but for any organism anywhere that is able to think. Neither humans nor little green aliens from another galaxy must be able to meddle, just by thinking alone, with empirical methods or our perceptional and conceptual processing of their results.

What holds for natural entities applies a fortiori to supernatural entities. We must stipulate, then, that no supernatural entity manipulates either the experimental setup or our mental (neuronal) processes or both.[25] We can even make the case that this holds not only for science but for perception and cognition in general. Indeed, this "no-supernature principle" as we may call it is also needed to avoid Cartesian skepticism. In his *Meditationes*, Descartes (1641) wrote:

> I will suppose, then, not that Deity, who is sovereignly good and the fountain of truth, but that some malignant demon, who is at once exceedingly potent and deceitful, has employed all his artifice to deceive me; I will suppose that the sky, the air, the earth, colors, figures, sounds, and all external things, are nothing better than the illusions of dreams, by means of which this being has laid snares for my credulity.... (*Meditation* 1, §12)

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[24] The no-psi principle was one of Broad's (1949) so-called basic limiting principles of science. Being a strong believer in the paranormal, Broad maintained that this basic limiting principle had been refuted by parapsychology. However, Broad was fooled by the sloppy and partly even fraudulent parapsychological research of his time.

[25] This was already acknowledged by J. S. B. Haldane (1934), who stated that his "practice as a scientist is atheistic," that is, when he sets up an experiment, he assumes "that no god, angel, or devil is going to interfere with its course" (p. vi).

Unlike Descartes, we no longer have reason to believe that the supernatural is dominated by an all-good God, who, by his very nature, not only refrains from malicious manipulation but even functions as the guarantor of the truth of our cognition and thus our knowledge.[26] Even in traditional Christianity, there are many other supernatural entities than God, like devils, demons, and angels. Now add the many supernatural entities of other religions and finally everything we can imagine. As the fantasy and horror movie genre shows, the possible inhabitants of supernature are only limited by our imagination. If we admit the supernatural, there is no reason to rule out a priori the existence of a malicious entity that could meddle with the world including our cognitive processes. So we need to start with the postulate that no such entities exist.

Let us summarize then the metaphysical suppositions of the general empirical methods of science:

(a) Ontological realism
(b) The (ontological) lawfulness principle
(c) The ex-nihilo-nihil-fit principle
(d) The antecedence principle and an ontological conception of causation
(e) The no-psi principle
(f) The no-supernature principle

Whoever subscribes to empirical scientific methods and their function to generate evidence must also subscribe to these metaphysical principles: without them, what we are doing would not be scientific measurements or experiments but rather meaningless games. Thus, these principles are part of the ontology behind science's methodology. In a world that has these properties, science is possible.

It may be seen as problematic that the principles (c), (e), and (f) are formulated negatively. It would not be a problem, though, to reformulate the above in positive terms, for example, by offering a full-fledged metaphysical theory, elucidating the notions of property, thing, event, process, lawfulness, etc. (see Bunge 1977; Bunge and Mahner 2004; Mahner 2012). In the sense of an axiomatic definition, we could then claim that everything which works that way is natural, and that the only real existents are such natural things and events. The above negative principles, then, would simply be corollaries of such a metaphysics formulated in positive terms. However, for the sake of simplicity and convenience, I shall stick to the negative formulations.

Now, are these principles also necessary conditions, perhaps even a priori conditions? Or could the scope of at least some of these principles be somewhat restricted while science could still work successfully? In other words, are they just default principles? For example, the traditional metaphysical principle of strict causality (every event has a cause) has been shown by quantum physics to be false, because some events such as radioactive decay are spontaneous (uncaused). This is why a

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[26] As Fales (2010) argues, even God may not know whether his thinking is manipulated by some evil demon. Does this require a second-order God of higher power who guarantees the truth of God's knowledge? If so, we would end up with an infinite regress of truth guarantors.

principle of strict causality is not part of the above list. And if the universe had popped out of nothing (however magical this would be), principle (c) would still hold within the universe. This suggests the possibility that some metaphysical principles could be revised. Similarly, it may be argued that even if the universe were initially created by a supernatural being, science would still be possible if there had been no further interventions since or if the number of interventions were very small. As our focus here is on metaphysical naturalism, the principles (a)–(e) will not be further addressed, so that we turn right to this possible objection to the no-supernature principle.

56.4.2 Naturalism or Noninterventionism?

We have just seen that observation, measurement, and experiment must not be subject to supernatural manipulation because they would then lose their status as empirical methods for the generation of evidence. Does this really warrant a no-supernature principle? Prima facie, it does not, at least not without further ado: it seems to warrant at most a principle of nonintervention with respect to scientific research and cognitive processes. How, then, can we justify a no-supernature principle?

To see how, it will be helpful to take a closer look at the definition of noninterventionism. It may be tempting to analyze it as a conditional statement such as "If supernatural entities exist, they do not intervene in the course of the natural world." However, this would turn nonintervention into a necessary condition for the existence of the supernatural. Indeed, by contraposition, we would obtain the absurd statement, "If supernatural entities intervene in the course of the world, they do not exist." Therefore, we better analyze "noninterventionism" as the conjunction of two statements, namely, "Supernatural entities exist really & Supernatural entities do not intervene in the course of the natural world."

This analysis shows that while at first sight noninterventionism appears to be a reasonable minimal supposition, it is in fact not, because it presupposes the existence of supernatural entities. The first statement of the above conjunction, "Supernatural entities exist," cannot be a metaphysical supposition of science because there is no reason why science should postulate the existence of something that, by not intervening in the course of the natural world, plays no part in any scientific explanation of the world.

Indeed, it is common practice in science to adopt the null hypothesis until there is evidence for an alternative substantive hypothesis. The null hypothesis usually negates that something is the case, such as that something exists or that two variables are related. Examples are the following: "Junk food is not the cause of obesity," "Men and women do not perform differently in mathematical tests," or "The Loch Ness monster does not exist." In order to prove some substantive hypothesis, its corresponding null hypothesis must be refuted empirically. The null hypothesis approach is not restricted to science: it is also adopted in modern law where a defendant is presumed innocent until proven guilty. Mutatis mutandis, the null hypothesis principle may – nay, should – be applied also in metaphysics, in particular when it comes to existential claims. For example, in the philosophy of religion, Antony Flew (1972) was the first to suggest defining "atheism" in this sense, although he did not use the scientific term "null hypothesis." An atheist, then, is not someone who positively and dogmatically denies the existence of gods, but someone who just adopts the "presumption of nonexistence" as a court of law adopts the presumption of innocence. Correspondingly, one way to conceive of metaphysical naturalism is as a metaphysical null hypothesis, stating that a supernature does not exist.[27]

Of course, there is an important difference between scientific and metaphysical null hypotheses; the latter are usually regarded as unfalsifiable by direct empirical evidence. This distinction at least was the upshot of both the neopositivists' and Popper's demarcation efforts. If we disregard the neopositivist view that metaphysics is untestable because it is nonsense, and thus accept Popper's distinction for the time being, we can say that at least some metaphysical hypotheses can be refuted (or, more cautiously, disconfirmed) *indirectly*, for example, by turning out to be incompatible with scientific practice or in being unable to explain it. For example, science could fail as a cognitive enterprise, either in its entirety or in some particular area, so that we would have to reconsider metaphysical naturalism.

In any case, the notion of a metaphysical null hypothesis implies that even metaphysical assumptions remain fallible in principle. At the same time it allows us to consider metaphysical naturalism as a necessary condition of science: if metaphysical naturalism fails, science fails too.

56.4.3 The Metaphysics of Supernaturalism

It appears that the supernatural can be characterized by simply negating most of the metaphysical principles listed in Sect. 56.4.1. Thus, a supernatural entity would be one that:

- May be able to create things out of nothing or annihilate them
- May not be subject to the antecedence principle in that it could make past events undone or change the natural sequence of events
- May not be subject to the lawfulness principle because it may be able to change the lawful properties of (natural) things or the lawful course of (natural) events
- May be able to influence (or to manipulate, if not fully control) natural things, including thinking entities and their perceptions and conceptions

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[27] In his debate with Plantinga, Dennett has recently called naturalism a null hypothesis (Dennett and Plantinga 2011, p. 49). Plantinga had argued that science is compatible with theism, because science doesn't explicitly state that there is no God. This shows that Plantinga is not familiar with the concept of a null hypothesis. The same seems to apply to Flanagan (2008, p. 437), who argues against "imperialist naturalism" that we would simply not know everything that there is or is not. Yet this is exactly the reason why we have to start with naturalism as a metaphysical null hypothesis.

This is essentially what is behind the common characterization of a supernatural entity as one that has magical abilities and can thus perform miracles. Whether or not supernatural entities are subject to any supernatural laws (whatever these may be) is irrelevant here. All that matters is that, in principle, they could be able to interfere with the lawful course of natural events, hence also with our brain functions. This is why a supernaturalist ontology invites (and maybe even entails) a nonnaturalist epistemology and methodology in which special forms of cognition, such as revelation, religious experience, a *sensus divinitatis*, or whatever nonnatural ways of communication with the supernatural may obtain, are accepted as legitimate sources of knowledge and means of justification. For example, Ratzsch (1996) and Plantinga (2001) defend the idea of a "uniquely Christian science" or a "theistic science," respectively, so that there is no reason why a Christian should not make use of particular religious "methods" in science. These examples illustrate that methodology is not free of metaphysics. It comes as no surprise therefore that accommodationist scientists and philosophers, who reject metaphysical naturalism to make room for religion yet at the same time want to keep supernaturalism out of science, struggle hard to make a consistent case (see Sect. 56.5.3).

That the supernatural is characterized mostly, if not exclusively, in negative terms has been shown in more detail by Spiegelberg (1951). Even prima facie positive attributes of the supernatural turn out to be negative ones in that they are just denials of known natural characteristics. For example, "transcendence" is the negation of "immanence," that is, *not* being "located" within the confines of our spatiotemporal world. Or being a first cause is nothing but being an *uncaused* cause. And the few positive attributes such as omnipotence or omniscience are actually natural properties raised to an absolute degree. In this regard they are not fully supernatural – a statement that may require some elaboration.

Spiegelberg distinguishes two conceptions of the supernatural, quantitative and qualitative. In the former case supernatural entities are ascribed properties that differ from the natural only in degree, though often to an absolute degree. For example, a supernatural entity is more powerful than a natural entity, perhaps even all-powerful, or more knowledgeable, perhaps even omniscient.[28] The attributes of supernatural entities are then still conceived of on the basis of familiar natural properties. Thus, such conceptions are more or less anthropomorphic, which suggests that the quantitatively supernatural, if any, would still have to be spatiotemporal. By contrast, according to qualitative supernaturalism, supernatural entities are *categorically* different from natural ones, so much so that their properties are essentially mysterious, ineffable, and incomprehensible. God, then, is the *Wholly Other*, not someone or something to be understood even by the faintest analogy with anything known natural. Spiegelberg called these two types of the supernatural *overnatural* and *transnatural,* respectively (1951, p. 343). Whereas the overnatural seems to be somewhat intelligible by analogy with known natural properties, the transnatural is incomprehensible. To obtain or retain a modicum of intelligibility, conceptions of the supernatural usually combine overnatural and transnatural

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[28] Despite many theological defenses, the notions of omnipotence and omniscience are incoherent (Martin 1990), so that we have reason to reject characterizations of the supernatural that employ them.

features. This allows the believer to oscillate between these two conceptions, depending on his argumentative needs. Modern theology tends to reject a merely overnatural conception of the supernatural as being too anthropomorphic and seems to prefer a more "sophisticated" conception of the supernatural in terms of the transnatural. Yet the transnatural is defined but negatively.

Spiegelberg's philosophical analysis is backed by cognitive psychology, which has shown that there is a rift between theological conceptions of religious entities and everyday religion. The latter is inevitably anthropomorphic but needs the counterintuitive features of the theological conceptions as an attention-grabbing potential.[29] It has been shown experimentally, for example, that although everyday believers know the theologically correct properties of God, they do conceive him in anthropomorphic terms when it comes to working with the concept of God in an everyday context (Barrett and Keil 1996). Whatever theology does to transnaturalize religious entities, believers will inevitably revert to overnatural concepts that better match their natural intuitive thinking. If religion is anthropomorphism, as Guthrie (1995) argues, this comes as no surprise.

Now, it may be argued that science faces a similar problem. Scientific concepts are often counterintuitive too, so ordinary people tend to stick to their more intuitive common sense understanding of the world. As McCauley (2011) shows, in this sense there is a divide between reflective attempts at cognition (science and theology) and non-reflective, popular – or as he calls them – "maturationally natural" attempts (commonsense cognition and popular religion). At the same time, however, both theology and popular religion are characterized by an unrestricted use of concepts of (intentional) agency or causality, whereas both science and commonsense cognition make a rather restricted explanatory use of intentional agents, that is, restricting it to the behavior of higher animals including humans. McCauley reminds us to not just compare science and religion simpliciter but in the correct respects. What is relevant here, then, is the metaphysical divide between science and commonsense cognition on the one hand and theology and popular religion on the other – which is the divide between naturalism and supernaturalism. Whereas the metaphysical divide, if any, between science and commonsense cognition is small, it is wider between theology and popular religion – which is the divide between the overnatural and the transnatural. In any case, both the overnatural and the transnatural are incompatible with the metaphysical naturalism of science.

56.5 Metaphysics and Methodology

56.5.1 Evidence Is No Metaphysics-Free Lunch

If metaphysical naturalism is a metaphysical presupposition of science, science should be unable to deal with anything supernatural. By contrast, if one believes that science is free of metaphysical presuppositions, the answer to the question of

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[29] See Boyer and Walker (2000), Boyer (2001), and McCauley (2011).

whether the supernatural is testable is quite simply affirmative. For example, if angels descended from the sky and raised the dead or if studies on the effects of intercessory prayer yielded significant positive results, we would have empirical evidence for the supernatural and hence a valid test. (In the first case, we would have *direct* evidence, in the second case *indirect* evidence.) While many authors agree with this view,[30] others maintain that the supernatural is untestable as a matter of principle.[31] This disagreement can be explained by the distinction between the overnatural and the transnatural.

Those who maintain that the supernatural is testable seem to conceive of the supernatural as merely overnatural. That is, the supernatural is intelligible to a certain degree because its properties are not actually categorically different from natural properties: overnatural entities are more or less superpowered entities with quasi-natural properties. By contrast, those who believe that the supernatural is untestable seem to regard the supernatural as transnatural and hence as categorically different from anything known natural – which makes it both inaccessible and unintelligible and thus untestable.

But let us first take a look at the two central concepts of this debate, testability and evidence. In the broad sense, a statement, a hypothesis, a model, or a theory is empirically testable if there is empirical evidence for or against it (Bunge 1983), whereby the evidence e is another statement – a datum – that is relevant to the hypothesis h (or model or theory) in that e either confirms or disconfirms h. Now both e and h must be semantically meaningful (nonsense is untestable), and they must not be logical truths or falsities. For some evidential statement e to be relevant to some hypothesis h, e and h must share at least one referent or, if preferred, one predicate. For example, data about the crime rate in Australia in 2011 are irrelevant to quantum theory, because the data and the theory are not (partially) co-referential. Last but not least, we must demand that e has been acquired with the help of empirical operations that are accessible to public scrutiny, and – here enters metaphysics – both the empirical operations and our cognitive processes involved in the perception and processing (interpretation and evaluation) of the data gained by these operations must involve only lawful natural processes – that is, they must not be the result of supernatural manipulation.

So for there to be some evidence e about the supernatural, e would have to share at least one predicate with the respective hypothesis h referring to some supernatural entity. This, in turn, would require that the supernatural referred to in h possesses at least one property that can be represented by a meaningful (positive) predicate – which could only be a natural or quasi-natural property. But this is possible only if the supernatural is conceived of as *not* qualitatively or categorically different from the natural. For example, if we found reproducible significant positive effects of intercessory prayer and if these empirical data were supposed to function as evidence for a hypothesis involving a supernatural being as the cause of this effect, the

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[30] See, e.g., Augustine (2001), Boudry et al. (2010, 2012), Fales (2010), Fishman (2009), Monton (2009), Stenger (2007), and Tooley (2011).

[31] See, e.g., Forrest (2000), Pennock (2000, 2001), and Spiegelberg (1951).

supernatural entity referred to would have to be able to "listen" to prayers, if only telepathically (however this would work), and understand and consider them in a way that is analogous to a human person listening to the requests of others and considering them on the basis of his or her background knowledge including a code of ethics. It is not intelligible how some solely negatively characterized transnatural entity should be able to do any of that; worse, we would not even know or understand what it means that any such entity *does* anything. For this reason, there could be evidence at most for the more or less anthropomorphically defined overnatural, so that only the overnatural may be testable in the broad sense.

Therefore, Pennock (2000, 2009) is right when he says that for the supernatural to be testable, it would have to be understood in a naturalized way, and the supernatural would have to be able to partly naturalize itself (or simply be natural to begin with) so as to interact with the natural world. If some process were actually transnatural, we could not observe it, however indirectly. Think of transubstantiation. Or think of the theological concept of continuous creation, according to which everything is constantly recreated ex nihilo by God, from moment to moment, and thus sustained in its existence. Continuity of existence is therefore just an appearance, whereas the reality behind it is a continuous transnatural intervention.

However, we still have to consider the last condition of evidence mentioned above, namely, the one that prohibits supernatural manipulation. Even if some empirical data fulfilled the formal conditions of evidence – provided the supernatural is construed as overnatural – we are still faced with the paradoxical situation that the empirical operations employed to produce such evidence presuppose the nonexistence of the very entities whose existence is supposed to be confirmed by this evidence. It may be tempting then to retreat to a principle of nonintervention with regard to our cognitive processes. But on what grounds could we defend noninterventionism? Of course, we could come up with various ad hoc assumptions. For example, the powers of the supernatural entities involved could somehow be limited, God could guarantee local noninterventionism with regard to our cognition, or God could even be the ultimate cause of our cognition and thus guarantee its correct functioning. But would it be epistemically warranted to accept any of these ad hoc contrivances, unless they are independently testable, that is, unless they are more than just logical possibilities? I don't think so. For this reason, naturalism remains the metaphysical default position of science, so that we have good reason to reject prima facie evidence for the overnatural as long as not all alternative natural explanations are exhausted.

56.5.2 Scientific Explanations Must Be Naturalist Explanations

Scientific theories are assessed (among others) with respect to their explanatory power. A scientific theory is expected to explain a certain fact or domain of facts. That is, it is supposed to tell us how something came about or how something works. In so doing, it employs law statements or reference to mechanisms (Bunge 1983;

Mahner and Bunge 1997). For example, a theory of photosynthesis informs us about the physiological processes (mechanisms) by means of which plants use light to transform carbon dioxide and water into carbohydrates and oxygen. These mechanisms are specific enough to explain what they are supposed to explain. Thus, they cannot be used to explain, for example, how birds fly or how earthquakes occur, because the respective laws and mechanisms are quite different. Do theories referring to supernatural causes or entities comply with this requirement?

They do not – even if we focus on the supernatural in the sense of the overnatural because transnatural entities devoid of positive properties are incomprehensible and hence nonexplanatory anyway. At first sight, invoking an overnatural cause to account for some fact does seem to have explanatory power. For example, intelligent design creationists claim that the theory of evolution cannot explain how certain complex organs have originated. So they invoke a supernatural entity, an intelligent designer (who allegedly need not be but is in fact considered to be God himself) who either created the organ or at least helped to accrue the given complexity. This answer appears to have explanatory power because, by analogy with human handicraft, we all understand what creating or developing artifacts is about. Yet in fact, it explains nothing because it explains too much. The problem is that an answer like "God made it the way it is" can be applied to all facts.[32] Whatever exists and whatever happens can be explained thus by reference to the will and actions of some supernatural entity. But an explanation that explains everything explains nothing.[33] Thus, supernatural explanations explain nothing because they are omni-explanatory.

The all-purpose God-did-it explanation is not something naturalists have come up with to ridicule supernaturalism. As a matter of fact, the philosophical doctrine of *occasionalism* seriously held that God is the cause of each and every event because matter is passive and cannot change or bring about anything on its own. If occasionalism, assuming 100 % supernatural causation, were true, there would be no need for natural explanations at all: a single supernatural cause would explain everything. So why do supernaturalists not adopt occasionalism? Why is science allowed to come up with natural explanations in some cases, but not in others? It seems that since the naturalist approach of science has been so successful, many supernaturalists have conceded its explanatory power and retreated to a god-of-the-gaps approach.[34]

Even some philosophers defend this view (e.g., Monton 2009), claiming that it is legitimate *in some cases* to fill an explanatory gap with a supernatural explainer, and that this would refute the charge that supernaturalist explanations are

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[32] More on the problems of supernaturalist explanations in Pennock (2000), who also explores the consequences of supernaturalism for the legal system, which would have to reconsider the-devil-made-me-do-it arguments including historically superseded forms of evidence based on "higher insights" and revelations.

[33] Note that the famous "theory of everything" in theoretical physics is a misnomer, because it would not explain everything. It would just offer a unified theory of the fundamental forces of physics. But this would not even begin to explain all the emergent properties of higher-level systems.

[34] Those supernaturalists who dislike the god-of-the-gaps approach for theological reasons have retreated to a transnatural conception of the supernatural, which is immune to any empirical refutation.

omni- explanatory. However, it is doubtful that this rejoinder works. After all, supernaturalist explanations come with two proliferation problems. First, if we admit one supernatural entity into the explanatory realm of science, we are on a slippery slope to admitting as many as we fancy (Kanitscheider 1996). Christian creationists, for example, will of course tell us that the number of supernatural entities is limited by scripture. But if science admits entities from the biblical cosmos, nothing prevents it from admitting entities from other religions as well. There is no a priori reason why a Christian supernatural entity is a better explainer than a Hindu one, for example. The more supernatural explainers we get, however, the closer we get to omni-explanation again. Second, even if science were able to incorporate the overnatural into its explanations, how do we know that reference to such entities provides ultimate explanations? If science could study the overnatural, what would happen if we encountered explanatory gaps in the overnatural world too? The analogous procedure would be to resort to super-supernatural entities to fill these gaps in the first-order supernatural world, and so on, possibly ad infinitum. Just think of the famous question, “Who created the creator?”.

In any case, there is another and perhaps better reason for rejecting supernatural explanantia than their omni-explanatory power. As we know nothing about the laws and mechanisms, if any, of the supernatural, we better argue that supernatural explanations explain nothing, not because they are omni-explanatory but because they are pseudo-explanatory. Indeed, to explain the unknown by means of something even more unknown and, worse, something magic and occult is an argumentative flaw known as *ignotum per ignotius* or *obscurum per obscurius*. Of course, believers in the supernatural may object that they do know something about the supernatural, for example, by reading sacred texts, by revelation, by some special form of experience, or by simply having some special insight or epistemic faculty such as a *sensus divinitatis*, as claimed, for instance, by Plantinga (2011). However, all these “methods” are no longer acceptable because they are arbitrary: just any claim could be justified by them, and they are not intersubjective.[35] For this reason, appealing to the supernatural for explanatory purposes is tantamount to saying that we do not know how a certain fact works or has come about. Supernatural explanations are therefore *argumenta ad ignorantiam*: appeals to ignorance (see also Smith 2001). Thus, they cannot, as Clarke (2009) claims, function as inferences to the best explanation: proposing a pseudo-explanation is an inference to the worst explanation.

For those who believe that filling explanatory gaps with supernatural entities is a legitimate instance of an inference to the best explanation, hypothesizing supernatural entities is analogous to postulating unobservable (or theoretical) entities in science. However, this idea faces several semantic, methodological, and ontological problems.[36]

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[35] See, e.g., Mackie (1982), Martin (1990), Forrest (2000), Fales (2010), and Philipse (2012).

[36] Philipse(2012) has recently shown that the inference-to-the-best-explanation approach of natural theology faces insurmountable problems, including the failure of Bayesianism, which is also championed by radical empiricists (e.g., Fishman 2009), who believe that scientific methodology has no metaphysical presuppositions.

In science, we must be willing to endow theoretical entities with a definitive set of properties. We cannot infer a best-explaining entity whose properties may vary arbitrarily (Kanitscheider 1996). Yet this is exactly the case with concepts of supernatural entities, in particular the concept of God, which is of course the most employed concept in supernaturalist explanations. Indeed, the properties of "God" vary from theologian to theologian, from tradition to tradition, even from believer to believer, so much so that "God" in theology *A* may have properties contradictory to the ones of "God" in theology *B*. A historical example is the God of Leibniz and Newton (Kanitscheider l.c.). Whereas Leibniz's God has set up the laws of nature at the beginning so that the world has been functioning without intervention ever since, Newton's God had to intervene more or less often in the natural world in order to adjust some imperfections. Thus, both a perfectly lawful and an imperfectly lawful world can be explained by reference to God. Whatever the factual evidence, then, some concept of God can always be applied.[37]

This is not to say that "God" is meaningless in the ordinary language of a certain group, because everyone has a rough idea of what "God" means in his or her religious tradition, in particular since these traditions employ rather anthropomorphic and thus overnatural conceptions of God. But this meaning is very restricted, as it is well known that religious sects have fought each other to death over the proper meaning of "God." However, being possibly meaningful locally and in ordinary language is not enough to qualify as a legitimate scientific concept and not even as a philosophical one. As Flew (1972) put it,

> Where the question of existence concerns, for instance, a Loch Ness Monster or an Abominable Snowman, [the introduction and defense of the proposed concept] may perhaps reasonably be deemed to be more or less complete before the argument begins. But in the controversy about the existence of God this is certainly not so: not only for the quite familiar reason that the word 'God' is used – or misused – in many different ways, but also […] because it cannot be taken for granted that even the would-be mainstream theist is operating with a legitimate concept which theoretically could have an application to an actual being.

This is important to remember because some scientists and oddly enough even some philosophers (like Monton 2009) seem to be so naive to think that the very use of the word "God" already amounts to postulating a legitimate theoretical entity with explanatory power. But it must first be ascertained that a sentence like "God caused some *x*" is more informative than "Tok caused some *x*" (Nielsen 1985).

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[37] It may be argued that the variation in the meaning of "God" is not problematic, because scientific concepts often start out with fuzzy and variable meanings too. Think of terms like "gene" or "atom." However, the variations in the precise meanings of these concepts are adjustments guided by empirical research and theory development. These concepts could be made precise enough to even get hold of their referents: today, genes can be sequenced, and atoms can be photographed. The various concepts of God, by contrast, are not constricted and guided by empirical research, so there is no improvement in the sense of an approximation to reality. The conceptual "development" in theology is purely apologetic in that the traditional overnatural concepts of God have been transformed into transnatural ones, so that they can no longer conflict with science, or anything factual for that matter.

Assuming for the sake of the argument that it is possible to make "God" more informative than "Tok" and thus turn it into a meaningful theoretical concept and also into one whose meaning does not vary arbitrarily, an explanation referring to this God would still be arbitrary. For example, the origin of a complex organ such as the vertebrate eye may be explained by reference to some creative intervention by God. But in fact reference to any other supernatural entity would do the same explanatory work, be it a devil, an angel, a demon, or whatever. After all, we know nothing about the possible powers and intentions of such entities. So we have no empirical means for deciding among competing supernaturalist explanations (Augustine 2001). The only commonality supernatural explanantia for some fact *x* seem to share is this: some supernatural entity chose to do *x* for unknown reasons. This is hardly superior to "we do not know what caused *x*."

For all these reasons, postulating supernatural entities is *not* analogous to postulating theoretical entities in science. The semantic fuzziness, if not arbitrariness, of supernaturalist terms makes them useless as scientific concepts.

In sum, the semantic and ontological problems of supernatural concepts and statements affect both the concepts of evidence and explanation. Even if there were highly anomalous data, they would not constitute evidence for the supernatural unless there were scientifically meaningful statements about the supernatural in the first place. Until then, all we could state perhaps is that something spooky is going on, but such anomalous data could not be explained as the results of some supernatural intervention. This holds a fortiori when we are not even faced with anomalies. For example, a sentence such as "Due to its complexity, the human eye was intelligently designed by a supernatural creator" is at first sight meaningful by analogy to human design and creation. But even when applied to the merely overnatural, it is no longer clear what "intelligence," "design," and "creation" actually mean. Indeed, as Sarkar (2011) has shown, intelligent design "theorists" are unable to offer coherent and positive specifications of these concepts. This does not preclude that some overnatural concepts could be made more precise, but it shows that the road to evidence for the supernatural and the supposed benefits of its explanatory power are much rockier than the accommodationists believe.

56.5.3 Metaphysical Versus Methodological Naturalism

While it has become common knowledge that science goes together with naturalism, it is by no means commonly agreed upon what the exact nature of this relationship is. Compatibilist authors, for example, claim that science's naturalism is only a methodological naturalism, not a metaphysical one. Particularly in the philosophical context of the evolutionism/creationism controversy as well as in science education, which is concerned with *nature of science* issues, it has become common practice to distinguish methodological naturalism from metaphysical (or ontological or philosophical) naturalism and to claim that the former, not the latter, is the correct philosophical assumption of science. For the sake of convenience, let's abbreviate methodological naturalism by MN and metaphysical or ontological naturalism by ON.

Despite the popularity of MN, the characterizations of MN that we encounter in this debate are less than clear, so much so that we must guess what exactly MN is and how it differs from ON. Before substantiating this charge by taking a look at some of the most common definitions, it is important to point out first that, in this context, "MN" is used in a nonstandard way.

In philosophy, the standard meaning of "MN" is that philosophy ought to embrace the results of science and use some of its methods (weak MN) or that there is no unique philosophical method at all because only the methods of the natural sciences produce genuine knowledge (strong MN or strong scientism). In other words, weak MN states that science and philosophy are essentially continuous in that they pursue similar tasks with similar means, whereas strong MN leaves not much to do for philosophy.[38] By contrast,

> [i]n some philosophy of religion circles, 'methodological naturalism' is understood differently, as a thesis about natural scientific method itself, not about philosophical method. In this sense, 'methodological naturalism' asserts that religious commitments have no relevance within science: natural science itself requires no specific attitude to religion, and can be practised just as well by adherents of religious faiths as by atheists or agnostics. (Papineau 2007)

It is only this second meaning of "MN" that is relevant here, and it is this conception that in my view is ill-understood. The main problem is that it is unclear whether this MN actually is about scientific method rather than the metaphysics of science, in other words, whether it is a methodological (and hence an epistemological) view proper or whether it is just a covert metaphysical position, that is, a disguised form of ON. To illustrate this problem, let us take a look at some common definitions.

Pennock (2001) characterizes ON thus: "The Ontological Naturalist makes a commitment to substantive claims about what exists in nature, and then adds a closure clause stating 'and that is all there is'" (p. 84). By contrast

> [t]he Methodological Naturalist does not make a commitment directly to a picture of what exists in the world, but rather to a set of methods as a reliable way to find out about the world – typically the methods of the natural sciences, and perhaps extensions that are continuous with them – and indirectly to what these methods discover. (Pennock 2001, p. 84)

A commitment to method indicates that MN is epistemological. This is seconded by Forrest (2000), who tells us that MN is "an epistemology as well as a procedural protocol." Michael Ruse, by contrast, includes also ontological assumptions (lawfulness):

> On the one hand, one has what one might call 'metaphysical naturalism': this indeed is a materialistic, atheistic view, for it argues that the world is as we see it and that there is nothing more. On the other hand, one has a notion or a practice that can properly be called 'methodological naturalism': although this is the working philosophy of the scientist, it is in no way atheistic as such. The methodological naturalist is the person who assumes that the world runs according to unbroken law; that humans can understand the world in terms of this law; and that science involves just such understanding without any reference to extra or supernatural forces like God. Whether there are such forces or beings is another matter entirely and simply not addressed by methodological naturalism. Hence … in no sense is

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[38] For further varieties of naturalism, see, e.g., De Caro and Macarthur (2008) and McMullin (2011).

> the methodological naturalist … committed to the denial of God's existence. It is simply that the methodological naturalist insists that, inasmuch as one is doing science, one avoid all theological or other religious references. (Ruse 2001b, p. 365)

Ruse's characterization reveals the main motivation behind MN: to assure the religious believer that science and religion are compatible.[39] Thus, the nonexistence of the supernatural (or rather its positive complement, ON) is not among the metaphysical presuppositions of science; it is just prohibited to refer to it. MN, then, boils down to the methodological rule, "Do not refer to anything supernatural!". The assumption of lawfulness, by contrast, is an ontological postulate. So Ruse's MN combines ontological and methodological aspects.

Even more ontological is another characterization of MN by Pennock:

> MN holds that as a principle of research we should regard the universe as a structured place that is ordered by uniform natural processes, and that scientists may not appeal to miracles or other supernatural interventions that break this presumed order. Science does not hold to MN dogmatically, but because of reasons having to do with the nature of empirical evidence. (Pennock 2009, p. 8)

Now, assumptions about the nature, structure, and workings of the world are metaphysical, not epistemological, even if most of the reasons for them are based on methodology. Moreover, Pennock's emphasis on MN as being nondogmatic indicates that in "MN" the adjective "methodological" could have a different meaning than the standard one, which is in the sense of methodology as normative epistemology, that is, the branch of epistemology concerned with the justification of beliefs and knowledge and the evaluation of methods. The standard adjective "methodological," then, classifies a position as epistemological – in contradistinction to adjectives describing some other philosophical category, such as a logical, semantical, ontological, or ethical. Another usage of "methodological," however, is in the sense of "provisional," "tentative," or "hypothetical." In this sense, "methodological" (sometimes also just "methodical") indicates either that the position in question is not regarded as an a priori truth or that it is not held dogmatically.

Consequently, there are at least two interpretations of MN:

1. MN is a genuine methodological/epistemological view, not an ontological one.
2. MN is an ontological position, namely, ON, but it is held provisionally rather than dogmatically.[40]

In the light of what was said about ON in this paper, only the second interpretation of MN is acceptable, although it would turn the name "MN" into a misnomer. The preference of "MN" over "provisional ON" could be due to the prejudice that

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[39] That this is one of the main reasons behind MN has also been shown by Boudry et al. (2012).

[40] MN in the first sense can be held either dogmatically or provisionally. In the latter case, we may provocatively propose the name "methodological methodological naturalism," so as to point out the double meaning of "methodological." Note also that Boudry et al. (2010, 2012) distinguish intrinsic MN (in the sense of a defining feature of science) from provisional MN. The latter would be what I have just called methodological MN. Here I defend provisional ON as an intrinsic feature of science.

everything metaphysical is dogmatic. While traditional, and in particular religious, metaphysics often was dogmatic indeed, this is no longer true of a modern science-oriented metaphysics, which is fallible (Bunge 1977; Ladyman 2012). And even if modern metaphysics still were an a priori discipline, as some authors maintain (e.g., Lowe 2011), its rationalist claims would not be dogmas. For example, nobody would consider the modus ponens or the tertium quid as dogmas. This needs to be emphasized because some authors seem to confuse "a priori" with "dogmatic" (e.g., Fishman 2009, p. 814). The same would of course be true if only *some* claims of metaphysics were fallible, whereas *others* would be a priori.

If MN were indeed an epistemology, a procedural protocol, or a set of purely methodological rules, it would be a rather arbitrary choice of a protocol or of a set of rules, because it would not be backed up by a metaphysics. In a realist philosophy, being is prior to knowing. That is, the furniture and structure of the world must make cognition possible in the first place, and they must allow for the successful application of scientific methods. Hence, for a methodology to make any sense and to work successfully, there must be a metaphysics that helps to explain the functioning of this methodology. The methodology of science is therefore based on ON, just as the methodology of Plantinga's "theistic science" is based on supernaturalism.

However, if methodology cannot be separated from metaphysics, science is not religiously neutral. If science adopts ON in the sense of a metaphysical null hypothesis, it is not true that science is neutral on the existence of God, as most defenders of MN maintain (e.g., Scott 1998; Ruse 2001b; Pennock 2009). After all, the null hypothesis about some entity *x* states that *x* does not exist. Thus, science is committed to the "presumption of nonexistence" also with regard to God's existence.

56.6 Methodological and Other Conflicts

The preceding was one long argument to the metaphysical incompatibility of science and religion. It also mentioned several methodological conflicts arising from their disparate metaphysics. It may be helpful to recall them here and add a few further sources of conflict.

We have seen that the successful application of empirical scientific methods and thus the very concept of empirical evidence presuppose ON as a metaphysical null hypothesis. Whoever maintains that science can test supernatural hypotheses must find a way to resolve the paradox that any empirical test of any factual hypothesis presupposes the null assumption that supernatural entities do not exist. Most likely, an attempt at resolving this paradox will consist in some form of noninterventionism, but such an answer should not just consist in coming up with (untestable) ad hoc explanations as to why supernatural entities might refrain from such interventions: it should be a more principled approach, that is, a full theory. And, if scientific rather than philosophical, such a theory about noninterventionism should be independently testable. Yet any such test would in turn presuppose the very non-interventionist assumption….

Assuming for the sake of the argument that this paradox may be resolved, hypotheses involving supernatural entities would be empirically testable only in a limited way, namely, inasmuch as the supernatural is merely overnatural, that is, inasmuch as it has at least some natural properties. Insofar as religious convictions involve transnatural entities, they are untestable. Nonetheless, it is often claimed that even such convictions are testable. However, this often turns out to be terminological trickery, because in the context of religion, "testability" has nothing to do with empirical testability but with some alleged "experiential" or "existential" testability (Rolston 1987). Such "existential testability" is a wholly subjective notion, which is incompatible with the objective testability of science. Indeed, empirical testability undermines religion: "Because religion is an ostensible social relationship, it tends to be nonempirical, since openly testing a social relationship (…) undermines it. Testing therefore may be explicitly prohibited" (Guthrie 1995, p. 202f).

We have also seen that explanations referring to supernatural entities are either omni-explanatory or pseudo-explanatory. They are appeals to ignorance, and they may fill any explanatory gap by positing some supernatural intervention. Such "explanations," however, are arbitrary because any supernatural entity could do the same explanatory work as any other, and we may have no way to distinguish between competing supernaturalist explanations.

An important methodological incompatibility between science and religion is the latter's reliance on particular "methods" of cognition such as intuition, revelation, or religious experience.[41] Their characteristic is that they are inscrutable procedures, hence purely subjective ones. Thus, if such revelations or experiences are contradictory, there is no possibility to decide which of the alternatives is true – unless they yielded some specific factual statements that would be testable independently of the revelation or experience itself. From a methodological point of view then, they are not methods at all. However, whether such procedures are endorsed or not, religionists can always retreat to their faith when they wish to circumvent further rational and critical analysis. The difference between fundamentalist and more liberal religious views only lies at the point when such a retreat to fideism occurs (Bartley 1984; Kitcher 2004; Martin 1990).

Whereas the religionists' faith, i.e., the disregard and disrespect for evidence, is hailed as a virtue in their belief community, scientists are supposed to recognize that personal conviction or psychological certitude is no substitute for cognitive justification. The latter can only be achieved by objective evidence. Now, it may be objected that the history of science indicates that many scientists also stick to their hypotheses in an irrational manner, that they believe in them, and that they try to protect them against negative evidence. Granted. The difference, however, is that critical thinking and cognitive justification by empirical evidence belong to the ideals of the scientific community. If a particular scientist fails to comply with these ideals, he will be blamed by his peers, not praised. And if a hypothesis is not

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[41] For a defense of religious experience as a valid method, see, e.g., Alston (2004). For critical analyses of the concept of religious experience, see Fales (2004, 2010), Kitcher (2004), Martin (1990), and Proudfoot (1985).

accepted by the scientific community, because there is too much negative evidence counting against it and there are perhaps better alternatives available, it will not enter the fund of scientific knowledge. By contrast, retaining one's faith even under the most averse falsifying conditions is a praiseworthy ideal in religion.

Related to faith is the role of authority in religion. While authority in religion is a methodological category, it is not so in science. Smith (2012) has recently examined the role of authority in science and religion from a mostly cognitive science viewpoint, pointing out that there are parallels between science and religion in how information is passed down from the original authority to colleagues, thence to science or religious teachers, respectively, and finally to students. Even though in science we do learn from authorities, such as colleagues, teachers, textbooks, and papers, because we cannot check every fact ourselves, and even though as individuals we do accept scientific knowledge on the basis of such authority, this is merely a matter of psychology and sociology. The real arbiter in science is evidence cum the current theoretical state of the art. This constitutes the ultimate justification. In religion, by contrast, religious doctrines are justified not by evidence, but because some authority, such as God himself or some spiritual guru, *pronounces* them as true. Justification by fiat and justification by evidence are incompatible methodologies.[42]

It may be objected that in religion "faith" does not mean "acceptance of doctrines on the basis of authority instead of evidence," but rather "trust" or "commitment." In this sense, faith is an aspect of a social relation such as trust in some other person around us. Yet such faith in persons is based on evidence: we trust our family and friends because we have some prior experience that they are trustworthy or worthy of commitment. By contrast, we have no such evidence in regard to supernatural persons, as we do not even have evidence of their very existence. So trust (faith$_2$) in such entities presupposes that we have already accepted the claim of their existence on faith$_1$ (belief without evidence). So even if there are two different concepts of faith, faith$_2$ is based on faith$_1$, so that the notion of faith$_1$ cannot be escaped. And faith$_1$ remains incompatible with science.

A different area of conflict concerns incompatible views about matters of fact. The most well-known case is the evolution/creation controversy. Liberal religionists tend to downplay such conspicuous conflicts because they are restricted to fundamentalist religions or denominations, respectively. However, fundamentalism is widespread in the USA, as well as in the Islamic world. While fundamentalism may have not much intellectual merit, it certainly is a powerful and dangerous social force. The doctrinal incompatibilities between fundamentalist religion and science are well known, so we may focus on the question of whether or not there are remaining conflicts even with respect to more liberal religion.

Apparently, there are no doctrinal conflicts left between science and liberal religion. Many scientific theories such as those in quantum physics, electromagnetism, plate tectonics, or immunology do not pose any problems for liberal religionists.

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[42] Curiously, Smith (2012, p. 13) appears to realize this difference but he downplays it by saying that "in practice, however, the distinction is less stark." Yet practice is irrelevant: demarcation is first of all a matter of methodology. The cognitive and sociological similarities of learning on the basis of authority in both science and religion cannot attenuate the methodological conflict.

However, a clash between scientific theories and religious beliefs is bound to occur concerning the general cosmological views about man's (and woman's) place and status in the world, such as the evolution of *Homo sapiens*, the nature of mind, the existence of an afterlife, and the origins and social functions of religion. However liberal, religionists cannot admit that evolution has been a purely natural process (Rachels 1991; Plantinga 2011). If consistent, they must adopt at least a minimal teleological viewpoint, that is, they must posit that the evolutionary process has been guided from above and that it has a definite purpose, particularly, to establish a relationship between humans and some supernatural entity, e.g., a deity. Even if this view reduces to the claim that evolution is God's way of creation, it is at odds with evolutionary theory, because the latter makes no reference to supernatural entities and neither does any other scientific theory.

Curiously, Plantinga (2011) claims that evolutionary theory is compatible with theism, because God could have guided the process of evolution and even have caused particular mutations (see also Dennett and Plantinga 2011). Nothing in evolutionary theory would prohibit that. The supernatural is excluded only if evolutionary theory is paired off to naturalism – a union that Plantinga believes to be gratuitous. But this connection is not at all gratuitous because science is not free of metaphysics.[43]

The preceding considerations indicate that, if a religious methodology were applied in science and the scientific methodology in religion, the result would be mutual destruction. Science and religion are not only methodologically different but incompatible. The same holds for the metaphysics and the ethos of science and religion. Finally, insofar as religion makes factual statements about the world, there will also remain some doctrinal incompatibilities between religion and science. Thus, it is plainly false that, at least at a deep level, science and religion are not in conflict (O'Hear 1993). Actually, it is just at the deeper levels where the most conspicuous conflicts arise.

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[43] Even more curiously, Plantinga (2011) argues that evolutionary theory is incompatible with metaphysical naturalism (see also Dennett and Plantinga 2011). A premise of this counterintuitive claim is that naturalists adopt an instrumentalist view of evolution, according to which natural selection favors at most cognitive faculties adequate for survival, not cognitive faculties furnishing truth, whether absolute or approximate. A purely natural evolution, then, entails that our cognitive faculties are not reliable in the sense of truth tracking. Plantinga is aware of the objection that a frog which manages to catch a fly must have correctly represented some property of its environment. But he claims that, even in the case of humans, the naturalist can talk only of appropriate behavior, not of true beliefs. He supports his case by resorting to antimaterialist arguments from the philosophy of mind, maintaining that any materialist conception of the brain and its functions, whether reductive or emergent, allows at best for appropriate behaviors, never beliefs, let alone true beliefs. True beliefs, so Plantinga's presupposition, can be had only in a nonmaterialist conception of the mind and a nonnaturalist conception of evolution. And the naturalist, who believes in the truth of naturalism, is inconsistent because naturalist evolution does not allow for the very existence of true beliefs. The real conflict, then, is between evolution and naturalism, not theism and evolution or science in general. Yet as evolutionary epistemology shows (Vollmer 2005), which is ignored by Plantinga, the evolution of cognition does lead to approximately true representations of the world (see also Dennett's reply in Dennett and Plantinga 2011). Also, naturalism requires a reconceptualization of concepts such as "knowledge" and "belief," which renders the antimaterialist argument moot (Bunge 1983).

56.7 The Conflict Between Science Education and Religious Education

> Even in his ability to be trained, man surpasses all animals. Mohammedans are trained to pray five times a day with their faces turned to Mecca and never fail to do so. Christians are trained to cross themselves, to bow, and to do other things on certain occasions. Indeed, speaking generally, religion is the chef d'œuvre of training, namely the ability to think; and so, as we know, a beginning in it cannot be made too early. There is no absurdity, however palpable, which cannot be firmly implanted in the minds of all, if only one begins to inculcate it before the early age of six by constantly repeating it to them with an air of great solemnity. For the training of man, like that of animals, is completely successful only at an early age. (Schopenhauer 1974, p. 603)

If science education is expected to inform students not only about facts but also about the philosophical background of science, it will have to address the methodological and metaphysical suppositions of science and maybe even all the world view components of science.[44] Inasmuch as religious education is also concerned with world view aspects, and we may claim that conveying a world view is even its major task, there is bound to be a conflict with the naturalist world view of science. After all, a religious education will have to state that the philosophical view of science is narrow or restricted, whereas the metaphysical and methodological outlook of religion offers so "much more" to discover. Indeed, defenders of religion argue that science and religion can be made compatible by choosing a broader metaphysics than naturalism (Barbour 2000), which entails of course that what science education teaches with respect to its philosophical foundations is inadequate.

The same holds for methodology. Religious education is likely to go against science education by allowing for exceptions concerning the acceptance of beliefs: religious beliefs need not be based on evidence, but may or even must be accepted on faith$_1$. Similarly, while it is a goal of science education to teach that it is appropriate to change one's views in the light of new evidence, religious education is prone to bringing forward a dogmatic mind-set because it teaches that unwavering faith is a good thing (Martin 1997).

Many evolutionary and developmental psychologists maintain that magical and religious thinking comes more natural because it is based on intuition rather than reflection, whereas critical or scientific thinking is something that has to be learned by keeping in check and overcoming our natural inclination towards superstitious thinking.[45]

Reinforcing our natural tendency for magical thinking by religious education thus appears to be antagonistic to the goals of science education. For example, while young children learn to master natural causality, they are at the same time exposed to religious concepts such as prayer, which teaches them that sheer wishing could

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[44] See Davson-Galle (2004), Irzik and Nola (2009), Matthews (1992, 2009), and Smith and Siegel (2004).

[45] See, e.g., Guthrie (1995), Boyer and Walker (2000), Boyer (2001), Dennett (2007), McCauley (2011), and Shermer (2011). For a different view, see Subbotsky (2000) and Woolley (2000), who consider children's minds as neutral and thus to be filled with either rational or irrational cultural input.

have a physical effect. It seems that children somehow manage to put natural and imaginary causation in different "mental compartments" so as to avoid confusion (Woolley 2000). Even so, we may suspect that this compartmentalization is only partial and thus remains a steady source for ontological confusions, leading to a greater temptation to believe in various supernatural or paranormal claims and theories. Indeed, there is growing evidence that religious believers are more prone to also believing in the paranormal.[46]

If we want to raise responsible citizens who ground both their private and political decisions on scientific rather than illusory information, it is counterproductive to expose them to illusory world views. Worse, they not only learn that it is alright to accept such views as true but also to act according to those illusory beliefs. It comes as no surprise therefore that analytical thinking reduces religious belief (Gervais and Norenzayan 2012), which invites the conclusion that the converse is true too.

It may be objected here that, as the case of religious scientists shows, religion neither impedes scientific understanding nor prevents believers from choosing a career in science (see, e.g., Cobern et al. 2012). However, the empirical situation is not as straightforward.[47] Unsurprisingly, the effects of religious education very much depend on the degree of one's religiosity: the more seriously people take their religion, the worse the effects. For example, Christian fundamentalist students suffer from a lower complexity of thought and thus achieve lower educational attainment (Hunsberger et al. 1996; Sherkat 2007). In general, according to Evans (2011), religious believers take up a scientific career just as often as others. However, both scientific understanding and career choice are reduced when it comes to those scientific fields that interfere with religious belief, such as evolutionary biology and other areas that study human origins. Also, believers tend to deny scientific results if they have the impression that scientists pursue a moral agenda, for example, if scientists make recommendations for political action, as it may occur in the case of climate change. So it appears that orthodox religiosity does not lead to a general hostility towards science, unless the latter competes with central tenets of the given belief system – which shows, however, that there is a conflict with regard to a consistently scientific or else religious world view.

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[46] See, e.g., Humphrey (1999), Goode (2000), Orenstein (2002), Hergovich et al. (2005), Lindeman and Aarnio (2007), and Eder et al. (2010). Note that the relation between religious belief and belief in the paranormal is not straightforward but depends on many variables such as level of education, gender, church attendance, and even the nature of the paranormal claims. For example, whereas astrology is mostly ruled out by Christians, creationism is not; and regular church attendance seems to prevent belief in the paranormal, presumably because the more frequent contact with official dogma protects from belief in competing paranormal or supernatural claims, respectively.

[47] For example, if science is strongly associated with technology, as in the questionnaire of Cobern et al. (2012), it may not be surprising that even orthodox believers see not much conflict between science and religion, except for ideologically contentious issues such as creationism or embryonic stem cell research. After all, even fundamentalists are glad to reap the benefits of modern technology. More importantly, personal views about the relation of science and religion, or even career choice, do not answer the de jure conflict problem concerning a consistent world view.

That a high level of religiosity may have negative effects is perhaps better seen at the social level. Comparing societal health data of the strongly religious USA with the more secular democracies of Western Europe and Japan, Paul concludes:

> In general, higher rates of belief in and worship of a creator correlate with higher rates of homicide, juvenile and early adult mortality, STD infection rates, teen pregnancy, and abortion in the prosperous democracies (…). The most theistic prosperous democracy, the U.S., […] is almost always the most dysfunctional of the developed democracies, sometimes spectacularly so, and almost always scores poorly. (Paul 2005, p. 7)

Critics have pointed out that, concerning the USA, these correlations are in most cases better explained by its higher level of social inequality rather than its high rate of religious belief (Delamontagne 2010, 2012). Using the Human Development Index (HDI), Delamontagne confirms the finding that high religiosity is accompanied by higher levels of societal dysfunction. However, he does not find a significant difference in HDI scores between moderately religious believers and nonbelievers, where the "moderately religious" are those for whom religion is "somewhat important" and the Bible is not true word by word, and who attend religious services but occasionally. Overall, higher levels of societal dysfunction in the USA are correlated with lower educational attainment, lower income, and race (Delamontagne 2012). While this may be correct sociologically, it is interesting to note from an ethical point of view that the high level of religiosity in the USA does not seem to contribute to decreasing the high level of social inequality – which casts doubt on the self-image of religion as a moral enterprise benefitting society.

It should not go unmentioned that psychological and sociological studies also report some positive effects associated with religiosity. For example, religious students tend to be more sociable, show less substance abuse problems, and tend to be more disciplined with respect to their coursework (Donahue and Nielsen 2005; Sherkat 2007). As the members of many denominations tend to form closer-knit communities, these examples may be seen as beneficial aspects of social embeddedness rather than direct effects of religious education as such. But should we not expect anyway that religious education contributes to a better morality?

Indeed, probably the major argument for religious education is that it is indispensable for moral education, in particular as science is concerned with matters of fact, not values and ethics. However, the alleged connection between religion and morality does not withstand scrutiny. First, empirical studies have shown that, overall, religious people fail to behave more morally than nonreligious people (Spilka et al. 1985; Tan 2006). For example, they neither cheat less in tests nor are they less selfish. Overall, then, religious education has no distinctly positive effect on moral behavior, which we would have to expect if the main function of religion and religious education were an ethical one.

Second, the goals of a modern moral education include acquiring the attitude and the capability of modifying one's moral principles in the light of new experience, knowledge, and insight (Martin 1991). This aim is certainly antagonistic to the religious attitude towards moral norms. If moral norms are God-given, be it by direct command or by a created natural law, they cannot be questioned or modified: they can only be obeyed or disobeyed. Finally, philosophy has amply demonstrated from Plato on that religion cannot be the basis of morality anyway.[48]

A final point, just for the fun of it, so to speak: it appears that religiosity is negatively associated to sense of humor; the more so, the more dogmatic or authoritarian believers are (Saroglou 2002). A possible objection, analogous to the argument from religious scientists, is obvious: we all know religious people with a great sense of humor. But "it is possible that religious people have a good sense of humor *despite* their religiosity; and not necessarily *because* of it" (Saroglou 2002, p. 206).

The quick upshot is this: empirical research on religiosity shows that both people and societies are the better off the less seriously they take the contents of their religious belief systems. The more literal and dogmatic the religious beliefs, the worse; the more abstract and liberal – more bluntly: the fuzzier and emptier – the better. The reason for this is, as we have seen again and again, that science and religion or, if preferred, a scientific and a religious world view are metaphysically, methodologically, and attitudinally incompatible.

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[48] See, e.g., Nowell-Smith (1967), Mackie (1982), Martin (1990, 2002), and Rachels (1995).

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Part XII
Theoretical Studies: Science Education Research

Chapter 57
Methodological Issues in Science Education Research: A Perspective from the Philosophy of Science

Keith S. Taber

57.1 Introduction

Science education as an academic field occupies an interesting position as there can be something of a tension between its location within one type of academic setting (education, often considered a social science, but also drawing upon the humanities) and its strong links with the disciplines that are the target for that educational activity (i.e. the natural sciences). For one thing, education is primarily about teaching, which is a practical and professional activity, often considered to be as much a craft as a science (Adams 2011; Grimmett and MacKinnon 1992). So education as an academic discipline has strong links with education *as practised* in schools and other institutions 'of' education and seeks to learn about and inform educational activity in such formal learning contexts, as well as increasingly in various informal contexts where learners may be self-taught or learn through informal interactions that may not be primarily intended to bring about teaching.

For the purposes of this chapter, education will be considered to be centrally about the processes of teaching and learning (Pring 2000), acknowledging that the teaching may sometimes be in the form of self-direction of learning (Taber 2009a). So science education is a field that is centrally concerned with the teaching and learning of, and about, science and the scientific disciplines. Science education encompasses both teaching for the general population – science for citizenship, scientific literary – and for the preparation of future professional scientists (Aikenhead 2006; Hodson 2009; Holbrook and Rannikmae 2007; Laugksch 2000; Millar and Osborne 1998).

The nature of the work of teaching has raised interesting issues about the relationship between educational research and practice: issues about outsider versus participant research (Taber 2012b) and about the challenges of translating research

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that is often necessarily framed for the academic community into a form that can inform practitioners (de Jong 2000; Russell and Osborne 1993) – or alternatively, seeking to find ways to draw generalisable findings from local highly contextualised studies (Taber 2000).

In addition, educational research is usually undertaken with human participants and so is subject to ethical considerations that do not apply in the natural sciences (e.g. British Educational Research Association 2004). A common metaphor for science is along the lines of wrestling nature's secrets from her (Pesic 1999), but researchers are discouraged from seeing the collection of educational research data in this way. Indeed, objectifying the learner (or teacher) as a source of data, rather than considering them as a person participating in research, is usually considered inappropriate in educational work. (Ethical issues are considered further later in the chapter.)

These generic issues, which need to be faced by educational researchers wishing to influence educational practice, are often supplemented for science education researchers by questions raised by the juxtaposition of mindsets and commitments of two somewhat different disciplinary backgrounds. Education as an academic subject is often seen as a social science, and research training in education reflects this, with a major focus on the paradigmatic concerns and tensions that operate in social research. (Indeed, this is oversimplistic as some scholarship undertaken within education faculties fits within the behavioural sciences, and some educational scholarship is best seen as located in the humanities.) Yet science education, as a field, tends not to be populated exclusively (or even primarily) by social scientists choosing to focus on science education for their research topic. There is certainly a fair number of those, but many (and in at least some national contexts, most) of those who undertake research in science education have a background in natural sciences and often experience of teaching natural science subjects at school or a higher level.

Even when such a researcher takes on an identity as a social science researcher, this is often secondary to their established identity as scientist and/or science educator (Kind and Taber 2005). Yet, as will be discussed below, research training in the natural sciences is often somewhat different to research training in education and other social sciences. A further complication is that many of those undertaking research in science education who do not have a background of studying and teaching in the natural sciences actually have a background in psychology: a subject that itself straddles the disciplinary divide between natural and social sciences (Barrett 2009). This chapter will explore a range of issues about the nature of educational research (and the consequent implications for methodology), with a particular concern with whether research in science education can be considered scientific.

This focus is of interest for a number of reasons. The question of what can be encompassed within science, the demarcation question, has been of concern to some philosophers of science who have wished to distinguish science from pseudoscience (Lakatos 1970; Popper 1934/1959). The very adoption of the term 'social sciences' reflects an attempt to model disciplines like sociology on the natural sciences, leading to the questions of to what extent and in what ways are social sciences and natural sciences part of a larger ‘science’ (Kagan 2009). In addition are two complications referred to above: the diversity of educational scholarship and the professional identities of science educators.

Within education faculties, research and scholarship may take a wide range of forms, from completely nonempirical philosophical analyses and literary analysis of texts written for children to experimental studies carried out by educational psychologists following established ‘paradigms’ (which, in that context, in effect means an experiment design) and considering participants as interchangeable subjects from particular populations (normal 12-year-olds, dyslexic 9-year-olds, autistic secondary age boys, etc.). In some national contexts, science educators will be working as part of such diverse communities, whereas in other national contexts it is more common for science educators to be working as part of a science faculty – within a physics department, for example. Many science educators move into research in science education with a well-established professional identity as a scientist (or more specifically chemist, etc.) and/or science teacher and therefore bring expectations of what kind of activity ‘research’ is: expectations that will inform their understanding of the particular institutional context in which they are working.

57.1.1 The Programme for This Chapter

The present chapter will first consider the particular nature of educational research and the nature of the field of science education, before considering the question of whether induction into science education research reflects the process of induction into research in the natural sciences. The chapter then considers the logic of developing a research project and how in educational enquiry this involves a justifiable choice of methodology, which may have to be moderated to some extent by ethical considerations and which informs the construction of a specific research design drawing from a range of particular research techniques used in educational work.

The chapter then considers how best to understand the range of methodologies commonly applied in education in terms of the different ontological and epistemological commitments that may apply when enquiring into different kinds of research foci. This leads to the conclusion that science education is unlikely to develop the kinds of neat and somewhat self-contained research traditions often associated with research in the natural sciences, but rather that principled choices from a diverse repertoire of methods are likely to reflect the inherent nature of the research area – and that indeed such choices will be expected to shift as knowledge is developed in any particular area of research.

The chapter finally considers how despite the apparently ‘aparadigmatic’ nature of research in science education, conceptualising research traditions within the field in terms of Lakatosian research programmes is likely to support the research community in organising research in ways that can be seen as scientific, in terms of allowing judgements about progress and offering researchers more heuristic guidance about fruitful directions for research.

57.2 The Nature of Education and Educational Research

The philosopher of education, Richard Pring, has highlighted how educational research should focus on the core activities of education, that is, teaching and learning, suggesting that 'the distinctive focus of educational research must be upon the quality of learning and thereby of teaching' (Pring 2000, p. 27). However, Pring also acknowledged that this would go beyond the immediate classroom context to include research undertaken to 'make sense of the activities, policies and institutions' which were set up to organise learning (p. 17). That is, educational research commonly focuses on classrooms and learners but also encompasses studies exploring the policies that inform classroom teaching and how these are derived, developed and (often imperfectly) enacted. Research may also consider the governance and management of institutions such as schools, as well as the way that education, teaching and learning are understood in particular cultural contexts.

Education is the context for directed learning, and in formal educational institutions (such as schools and colleges), structures are put in place to encourage and channel learning. A key type of activity in such institutions is teaching, which I suggest is best understood as *deliberate actions intended to bring about particular learning* (Taber 2014). The conditional 'intended' is important here, because as the vast literature in science education testifies, what students learn is not necessarily what the teacher intended to teach (Duit 2009) and may sometimes be quite idiosyncratic. Not only is much learning spontaneous, in the sense of occurring without any specific intention to learn, but, as learning is a highly iterative process, it is strongly channelled by existing ways of understanding the world.

There is an interesting question of the relationship between terms such as teaching, pedagogy and Didaktik (Fischler 2011) – the latter being a common term in continental Europe, but used less in the Anglophone countries. Teaching is here used to refer to the activity, where pedagogy can either be used to refer to the general theoretical body of knowledge about how to go about teaching or to refer to a specific strategy adopted in a particular teaching context (an interesting parallel with the way 'methodology' is used both in a general abstract sense and to describe the specific strategy employed in a particular research study).

Learning is here understood as a change in the potential for behaviour, that is, a change in the behavioural repertoire of the learner (Taber 2009b), assumed to be underpinned by changes in the way the learner's experience of the world is represented in some form of cognitive structure. It is widely accepted that 'circuits' within the brain provide the material substrate that supports cognition, although the precise correlation between the synaptic level and experience of 'having an idea' is much less clear. Despite this, it seems that people do represent aspects of their experience of the external world internally and that, as Vygotsky (1934/1986) long ago noted, these representations are organised into structures rather than being like discrete 'peas in a pod'.

The nature (e.g. coherence) and extent of such structuring is a theme of empirical research in science education (Fellows 1994; Ganaras et al. 2008; Taber 2008), and it is clear that the ways individuals relate and integrate their conceptions of the natural world are often quite different from the way concepts are related in professional science or in formal science curricula. However, such conclusions are indirect inferences made in research, because an individual's cognitive structure is not directly observable (Phillips 1983). Rather, we rely on the learner's behaviour in representing their ideas in the 'public space' where it can be observed as the basis for modelling their thinking (Taber 2014). In science education, we are often concerned with developing students' knowledge and understanding (key concepts that are themselves not easy to operationalise in research), so commonly the 'behaviour' we are interested in is of the form of speech or inscriptions – such as are involved in answering a teacher's questions in class or completing a test paper or assignment.

Although some commentators consider informal learning, and the spontaneous mechanisms that support it, to be distinct from learning processes in educational contexts where there is an intention to teach particular things (Laurillard 2012), there is an increasing tendency for contexts for informal science learning (such as museums) to be planned according to pedagogic principles. So although informal science learning may often appear 'haphazard and incoherent' (Stocklmayer et al. 2010, p. 11), the educational work of museums and science centres is informed by similar debates and principles as those informing the design of curriculum and teaching in schools and colleges (Pedretti 2002).

As an academic area, education is something of a recent addition to the academy – despite scholarly periodicals such as *Science Education* (preceded by *General Science Quarterly*, which first appeared in 1916) and *School Science Review* (first appeared 1919) being long established – and this is reflected in the diverse disciplinary backgrounds of many education faculties as noted above. Traditionally education was seen as an applied subject which drew upon four 'foundation' disciplines: philosophy, psychology, sociology and history (McCulloch 2002). However, in recent decades, education has become more firmly established as an academic subject in its own right. There would seem to be a generational effect here, in that the first holders of PhDs 'in education' were necessarily supervised and advised by faculty who themselves originally trained in other disciplines; but that first generation of education PhDs could then start supervising their own research students from within the 'discipline' of education.

57.3 The Nature of Science Education in the Academy

Certainly in science education, this transition occurred within living memory of some of those currently still working in the field, so the most senior professors of science education active today undertook their own postgraduate studies in other subjects. Fensham (2004) has provided a very readable account of the origins of science education through this process. This means that early researchers in the field were trained in research methods of different disciplines, and for those who trained in the natural sciences, their expertise was often not optimal for transferring to a context exploring educational problems.

Some of the early studies in science education adopted methodology that would seem crude and naive to a postgraduate student (and are justified in terms that would be considered inadequate if submitted for publication) today, and there has been much borrowing of techniques from other fields. Such borrowing need not be a bad thing, providing the techniques concerned are not, in the process, decontextualised from the paradigmatic commitments which provided their justification as valid knowledge-seeking tools. To offer a crude analogy: a screwdriver can be used as a chisel, and a chisel can be used as a screwdriver, but in both cases, one is likely to do a poor job and risk the integrity of the tool itself. In the same manner, as will become clear below, research techniques have been designed with particular jobs in mind and may provide a messy outcome when used without due care and attention.

The major journals in science education now publish work not only on a wide range of themes but adopting a broad range of methodologies. Some of these methodologies reflect approaches common in the natural science, but others draw upon approaches less widely employed in the natural sciences, as they are intended to explore aspects of the human experience itself. Whilst the scope of the present chapter does not allow any detailed discussion of specific data collection or analysis techniques, the key considerations that have informed different paradigmatic stances will be considered below.

57.3.1 The Methodological Turn in Science Education

Early researchers in the field of science education were pioneers, and it is perhaps inevitable that some pioneering work seems crude or trite as a field becomes better established. However, recent decades have seen the development of an extensive literature focusing on educational research methodology, and a new researcher entering an educational field such as science education today can be introduced to a varied, if somewhat contested, range of reading, setting out the nature of educational research and how one should go about it. Often educational research is treated as a specialised area within social research (i.e. social science research) more generally, and sometimes it is grouped with other areas that relate to the professions (particularly areas such as social work and nursing). In effect, educational research has developed into a field of activity within education as a subject area, and research methodology has become the subject of primary journals (such as *Educational Research*er, ISSN: 0013-189X; 1935-102X) as well as being an active area of textbook publishing.

This reification of educational research into a subject for study as well as a means to carry out studies has led to much discussion about the diversity of methodological approaches used in educational studies and the relationships between them (Bassey 1992; Clark 2005). Some of these issues are explored later in this chapter. With this specific topics. Rather there will often be several theoretical perspectives that might be relevant to a topic. These might sometimes be seen as based on competing theories, but often they might be better thought of as each illuminating some of the facets of a complex phenomenon.

There are parallels to both of these alternatives in the natural sciences. So we might consider theoretical perspectives as competing in the way that (a) the oxygen theory of combustion competed with the phlogiston theory (Thagard 1992) or (b) the notion that species have an inherent essence that makes them absolutely distinct (as might be expected if each type was originally formed by an act of special creation) is at odds with the idea that all living things derive by descent from a common ancestor (in which case species are not absolute, but current loci of relatively stable forms at a particular historical moment, contingent upon a great many particulars of past events, with temporary salience against a background of constant slow modification and shifts).

But even in the natural sciences, alternative and apparently inconsistent perspectives need not be considered to be in direct competition. An analogy here might be the way interactions between colliding molecules might be conceptualised in terms of different theoretical models. One theoretical perspective that could be applied would be an ideal gas (i.e. kinetic theory) model, where molecules can be considered to behave as spheres that undergo perfectly elastic collisions. Here the molecules are stable entities, and their collective behaviour can be used in explanatory models of bulk behaviour of the gas. Another theoretical perspective that might be applied could be to consider molecules to be complex structures including electronic orbitals with associated energy levels, some of which are occupied and others unoccupied. Here descriptions in terms of potential overlap between occupied orbitals on one molecule and unoccupied orbitals on another may form the basis for explanatory models of reaction mechanisms (at the submicroscopic level) that help explain patterns of chemical reactivity at the bulk level. In this example, we might consider that both of these perspectives are potentially valid and could contribute to a full understanding of gas properties, but that, in relation to a particular scientific problem, one will be more productive than the other. So even within the natural sciences, the application of a concept may involve selecting an appropriate tool for a particular job, from a metaphorical conceptual 'toolkit' (Taber 1995) offering alternatives that all have their own range of application. Indeed, this very feature of science appears to offer a major challenge to many learners, presumably because they often misconstrue the nature of the models presented in the curriculum (Taber 2010c).

The difference between these two types of cases would seem to be whether the different perspectives can meaningfully be considered complementary. Whilst a model of molecules as like tiny billiard balls is clearly incomplete because it does not explain chemical reactions, it remains a useful analogy for some purposes and can complement other models that explain particle behaviour under other circumstances. In other words, the apparently inconsistent models are not competing for the same 'explanatory space' in this example: one perspective explains physical properties that are commonly exhibited by gases and gas mixtures, and the other perspective can explain why chemical change sometimes occurs when gases mix.

diversification of methodological approaches being employed in educational research, it has become increasingly expected that empirical research reports should provide not only a description of the methodology employed but also a justification of the approach used and acknowledgements of limitations inherent in the methodology or the specific design for a study.

These considerations might suggest that there seem to be two related key differences between methodology in education, including science education, and in the natural sciences:

1. Research in science education as a field draws upon a wide menu of available methodological choices, whereas research in most particular fields within the natural sciences is limited to a much more (to mix metaphors) limited palette.
2. Descriptions of research in science education often offer extensive justification of chosen methodology, commonly including explicit discussion of ontological and epistemological commitments underpinning research designs, whereas reports of research in the natural sciences often focus on specific technical details without extensive justification of the overall methodology.

This could be taken to suggest that research in science education, being unlike research in the natural sciences, should not be considered scientific in nature. To consider why these differences exist, it is useful to consider Kuhn's account of how researchers are inducted into the natural sciences.

57.4 Normal Science, Revolutionary Science and Another 'Sort of Scientific Research'

Thomas Kuhn has been highly influential in both science studies and discourse about the nature of work in the social sciences, largely based upon the reaction to his essay on *The Structure of Scientific Revolutions* (Kuhn 1970) and the adoption of the notion of working within a 'paradigm'. In that work, Kuhn argued that scientific revolutions were rare and that most scientists spent their careers doing what he termed 'normal science'. Although key aspects of this work have been much criticised (and some of this criticism will be discussed briefly below), Kuhn's description of how scientists are trained and inducted into traditions of research is especially relevant to the present chapter and is considered here to offer very fruitful insights when considering the way methodology is discussed and understood in educational research.

Kuhn described normal science as working within a paradigm or a 'disciplinary matrix' (Kuhn 1974/1977). In Kuhn's model, most science occurs within an established tradition, and these traditions are occasionally interrupted when a niggling anomaly leads to an individual (a) forming a revolutionary reconceptualisation of the field and then (b) persuading the scientific community to shift allegiance such that a new tradition is formed and the old one abandoned. For Kuhn such a revolution changes both the meaning of terms and ways of seeing and understanding the world to such an extent that those working within the new paradigm should be considered to speak a different language (such that the two paradigms become incommensurable) and in effect work in a different world (Kuhn 1996).

Aspects of this thesis have been widely discussed and critiqued (Masterman 1970; Popper 1994), especially the notion of incommensurability and the potential implication that there can be no objective way of judging progress in science – i.e. it could be argued from Kuhn's analysis that a revolution makes a field different, but not necessarily further advanced – although Kuhn himself argued that his analysis suggests judging progress is problematic rather than impossible (Kuhn 1973/1977).

57.4.1 Induction into Scientific Research

However the aspect of Kuhn's work most relevant for the present chapter is his description of how a new scientist prepares for work in, and becomes accepted within, a research field. For Kuhn, the process of becoming a professional scientist is in effect an induction into a particular tradition (or paradigm, in one of the senses in which Kuhn used the term) through a kind of intellectual apprenticeship. By the completion of this training process, the new scientist has adopted the norms associated with the disciplinary matrix that in effect defines the current state of the particular subfield in which the scientist has completed research training (Kuhn 1996). This disciplinary matrix provides the framework for scientific work 'based firmly upon a settled consensus acquired from scientific education and reinforced by subsequent life in the profession' (Kuhn 1959/1977, p. 227). Kuhn saw each such tradition as ultimately derived from a particular scientific achievement – such as Newton's work on mechanics or Lavoisier's work on chemistry, but other examples might be Darwin's work on natural selection or Crick and colleagues' work on the structure of DNA and the 'central dogma' of molecular biology. Such achievements were revolutionary enough to each initiate a new direction for scientific research; moreover, one which could provide a starting point for developing a whole new approach (Kuhn 1996).

In his work, Kuhn argued strongly that a scientist needed to demonstrate a commitment to the tradition in which he or she was working and that this was equally true for the few who would initiate scientific revolutions of their own, as it was for the majority that would work their entire careers on the 'mopping-up' work of normal science. Kuhn did not imply that such 'mopping-up' work lacked interest or excitement: it was routine in the sense of being within an established tradition and therefore had a strong 'convergent' focus, compared with the divergent nature of the 'discoveries' that initiated the occasional scientific revolutions.

Kuhn recognised the ubiquity of imprecision and anomaly in scientific work and considered that progress in science depended upon scientists being able to have enough commitment to the accepted theory in the field not to be continuously distracted by attempts to explain nonsignificant discrepancies between theoretical predictions and results (Kuhn 1961/1977). Michael Polanyi (1962/1969) also discussed how scientists need to be able to use personal judgement to ignore most of the multitude of apparent anomalies (in effect, prima facie refutations) met in the course of scientific work. Where Polanyi emphasised how such judgement depended upon tacit knowledge (which he related to the way an external reality becomes known through the complexity and subtlety of human perception/cognition), Kuhn stressed how the indoctrinating effect of scientific education could dull the ability to recognise a significant anomaly for what it was.

Whilst identification of a significant anomaly was central to initiating a scientific revolution in Kuhn' account, even the successful revolutionary has to make their argument for a paradigm shift from within the existing tradition – that is, they need to be recognised by others in the community working in the field as being a full legitimate participant (cf. Lave and Wenger 1991) in that particular scientific tradition (Kuhn 1996). This required a 'thoroughgoing commitment' to the existing tradition (Kuhn 1959/1977, p. 235).

The disciplinary matrix in which scientists work, and in which they draw upon the commitments underpinning their scientific work, supports 'relatively unproblematic…professional communication' and allows 'relative unanimity of professional judgment' that is 'comprised of ordered elements of various sorts' (Kuhn 1974/1977, p. 297). These included symbolic generalisations, models and exemplars (the latter providing the derivation of Kuhn's original choice of the term 'paradigm'). For Kuhn, the set of models used within a scientific tradition range from heuristics offering analogical insight to deeply held metaphysical commitments amounting to an ontology (Kuhn 1974/1977). Indeed, within normal science, 'research is directed to the articulation of those phenomena and theories that the paradigm already supplies' (Kuhn 1996, p. 24). Elsewhere, Kuhn refers to how researchers within a shared paradigm 'are committed to the same rules and standards for scientific practice' (Kuhn 1996, p. 11) and how paradigmatic exemplification derives from how scientific practice involves 'law, theory, application, and instrumentation together' (Kuhn 1996, p. 10).

As suggested above, Kuhn's thesis has not been universally accepted. Indeed, whilst it may be welcomed as a useful challenge to models of the nature of science that relied on the logical structure of research and oversold an assumption that in principle sufficient careful research could provide a basis for unambiguously interpreting nature, it arguably encouraged views of science that in turn underplayed the role of logical argument and interrogation of evidence in reaching consensus in science. In particular, the suggestion that normal science is somewhat routine, pedestrian and almost a matter of following algorithms (which has perhaps been taken from Kuhn, rather than offered by him) has been challenged by those who consider controversy to be a common if not constant feature of science, rather than a sign of a rare major shift (Machamer et al. 2000). Indeed, Feyerabend (1988) countered the notion of normal science by claiming that the history of science suggested there was no standard method or set of preferred approaches in science, but rather that scientists were much more pragmatic, adapting and inventing method to meet the needs of the problem at hand.

At first sight, there appears to be a wide gulf here, but perhaps such different accounts of science need not be as inconsistent as may appear initially to be the case. The basis for suggesting this (whilst acknowledging it may partly reflect a personal cognitive style of tending to prefer integration to fragmentation) links to notions of what might be termed 'grain' size in analysing the nature of science. This reading would acknowledge both (i) that controversy is certainly common in science and indeed is probably an important part of the motivation for much research (Machamer et al. 2000), but many controversies concern issues that are not linked to core ontological commitments within a research tradition (and so can be accommodated in something like Kuhn's normal science), and (ii) that innovative techniques for data collection and analysis are indeed common in the history of science when taking the 'long' view, but that again major new approaches (rather than refinements to existing techniques) are relatively rare within the day-to-day career of the working scientist, and that 'standard' techniques do become and remain established within research traditions.

From this view, criticism of Kuhnian normal science as a description of most scientific activity would *not* undermine what Kuhn has to say about the research training of individual new scientists, which generally takes place over a matter of a few years, working in one area of science and often within the context of one or two research teams and laboratories. Typically, then, according to Kuhn, a scientist is trained within a particular research tradition that leads to embracing the research community's commitment to the kinds of phenomena that fall within the scope of the field, the kind of entities that are used in explanations, a theoretical apparatus within which predictions and explanations can be developed, standard forms of representation, and accepted techniques for undertaking research studies. However, despite this characterisation of normal science, Kuhn did not claim that scientific work necessarily *had* to take this form, but rather saw this as the nature of 'mature' sciences.

Indeed, Kuhn (1996, p. 11) acknowledged that in fields that had not achieved such maturity, 'there can be a sort of scientific research without paradigms, or at least without … unequivocal and … binding' paradigms. That is, Kuhn was offering a descriptive account of science based on his historical scholarship, not a prescription for science. His description could be seen as providing demarcation criteria for mature sciences, but not for scientific enquiry per se. In 1983, Gilbert and Watts referred to how research into learning in science was in 'a pre-paradigmatic phase' as there was 'no general agreement on the aims of enquiry, the methods to be used, criteria for appraising data, the use to be made of the outcomes' (p. 61). Arguably, to some extent, this description could still be applied to science education as a field of research some 30 years later, and if we wish to see research in science education as a scientific activity, then we need to consider it as Kuhn's other, less mature, 'sort of scientific research'. However, there is an alternative argument, long recognised by Shulman (1986), for example, that suggests that research into such areas as teaching is unlikely to mature into something like Kuhnian normal science, because the degree of complexity of educational phenomena is such that no single perspective is likely to offer a full enough account of inform effective educational practice.

57.5 Characterising the Educational Research Project

In order to consider whether educational research is, is sometimes, or at least can be, a ‘sort of scientific research’, it is necessary to consider the nature of the work the educational researcher undertakes and to reflect on how and why this might be different from research in the natural sciences.

57.5.1 The Overall ‘Shape’ of a Discrete Research Study

The conceptualisation and development of an educational research project goes through two cycles during each of which there is a kind of expansion phase of exploring options and seeking sources of information, followed by a focusing (Taber 2013). Figure 57.1 uses the lemniscate as a visual metaphor to suggest that a study can be understood to ideally progress through three focal points (indicated on Fig. 57.1):

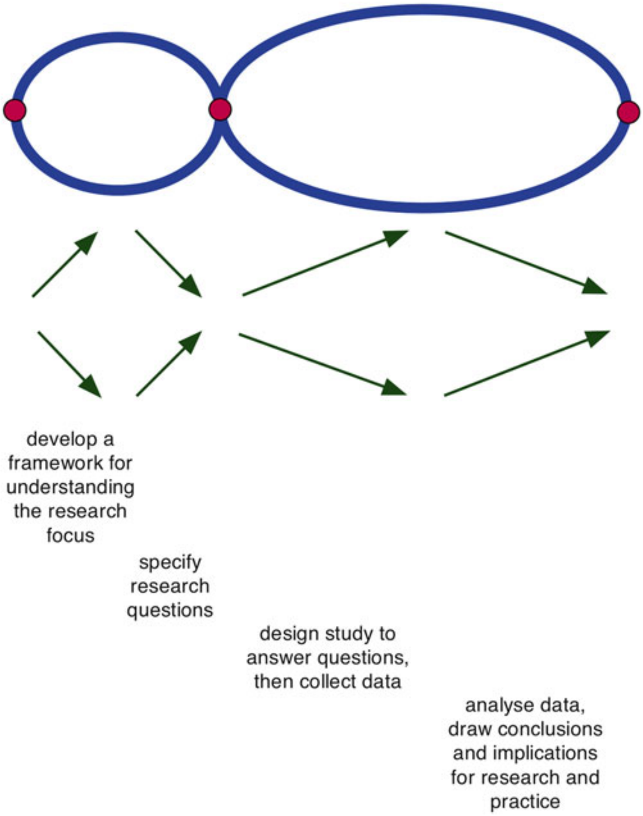

Fig. 57.1 The research process as involving successive phases of expansive and focused thinking

the initial concern or interest, the specific research questions (RQs) and the conclusions. This model assumes, for the moment, that research is largely conceptualised on a study-by-study basis, which is clearly a major simplification (Lakatos 1970).

The origin of the project is some kind of concern, issue or other focus that is seen worth investigating. The first cycle (see below) involves a process of developing the conceptual framework for the study – exploring relevant literature and reviewing previous research that may be pertinent – 'setting the scene' as it were for the new study. That is a phase that can be seen as supported by divergent thinking: allowing the recognition of relevance and forming links across diverse literature. This is followed by the framing of the particular RQ for the study. This latter step involves a focusing in on the specifics of the research (a more convergent process) and setting out how variables and constructs will be understood. Reaching this point will involve identifying any axiological commitments, the values that inform why we do research and so how we should conduct ourselves as researchers, as well as the ontological nature of what is to be researched, and so the epistemological constraints and affordances which will inform the kind of knowledge that it is possible to develop about what we are interested in.

The second 'cycle' of the project (Fig. 57.1) involves another expansive stage, where a research design is developed which can facilitate the answering of the RQ, followed by the collection of data to build up the evidence base needed to answer the RQ. This is followed by a further convergent phase where analysis 'reduces' data to results and leads to conclusions. The overall process therefore calls upon both divergent and convergent thinking: both creative and logical thought (Taber 2011).

57.5.2 *Owning the Research Problem in Science and in Science Education*

Formalising the process in these terms is often important in educational research because of the nature of existing literature. This reflects a difference between the common experiences of new researchers in education and those in natural sciences. A new doctoral student in one of the natural sciences will commonly be set a problem that is part of an ongoing programme within a wider research team in the laboratory and the process of identifying the relevant literature, and so conceptualising the 'gap' in existing knowledge the study is intended to 'fill' may be relatively straightforward. Indeed, it may be quite clear which techniques are to be adopted (perhaps those for which the lab is equipped with specialised apparatus) and how data will need to be analysed to produce knowledge claims acceptable to those working in the relevant field of science.

Arguably, the novice scientific researcher may be scaffolded to such an extent that they are only primarily responsible for the data collection and analysis stages, and much of the decision-making that leads up to this is largely channelled by the induction into an established way of understanding the ontology and epistemology adopted in that subfield of science. This would suggest that much of the thinking which informs such decision-making for a new researcher in education is in effect short circuited in the natural sciences. This is in line with the picture of 'normal' science (see above), described by Kuhn (1996), where the new scientist is inducted into the disciplinary matrix of the field by working through the standard paradigms. The result may often be someone who is very informed about the standard thinking and techniques in a specialised field, whilst having a much more limited knowledge of other fields within the broader discipline.

Yet the experience of a new doctoral student in education may be quite different in a number of ways. Whilst science education is now sufficiently theorised and staffed with expertise to support the natural science model outlined above, it is more likely that the research student will have greater latitude in selecting their project (if only because the apparatuses of research are less specialised and so less likely to be a constraint), and indeed within education the process of developing the project is seen as a key part of the education and training of the researcher. Moreover, whilst it remains important that doctoral supervision provides specialist support in learning about the topic area and acquiring specific skills, the student may find no single clear picture of the research area in the literature that allows an obvious conceptualisation of a 'gap' in the knowledge or a single sensible approach to an issue or problem. The state of knowledge in many educational topics would not fit Kuhn's notion of normal science, with its paradigmatic norms.

Where Kuhn suggests that the primary mode of thinking in normal science is convergent, this is often less true in educational research. Rather than being expected to 'plug' a specific 'hole' assigned by a supervisor, the educational research student is often expected to demonstrate extensive divergent thinking in accessing, evaluating and choosing between alternative potential ways of conceptualising their problem area. Within this context for undertaking research, the transition from an initial topic or issue of interest to the formation of specific RQ normally involves wide reading around a topic to appreciate and consider a range of possible ways of conceptualising the field, perhaps each based upon understanding the topic in quite distinct ways, and so suggesting different notions of how best to enquire into the subject. It is seen as the part of the student's task to develop a conceptualisation of the field and the justification for adopting (and if necessary adapting) a particular theoretical perspective (see below) for supporting the research. To caricature, the educational researcher 'owns' the research problem not because it has been 'given' (assigned) to them by the supervisor or lab director, but because they have 'built' (developed, discovered, constructed) it themselves.

Moreover, because of the lack of a clear disciplinary matrix that sets out particular tools for thinking about and doing research in the field, the research student is expected to learn about a wide range of methodologies so as to be able to comprehend and apply critical judgement to reading literature around the research topic, as it is quite likely that relevant knowledge claims in research journals will derive from a range of data collection and analytical techniques, potentially drawing upon very different (ontological and epistemological) assumptions informing different researchers' work.

The RQs themselves act as the point of transition in the flow of the study (see Fig. 57.1), and just as the RQs should reflect the thinking that has informed their formulation, they should themselves be reflected in what is to follow. A research design must address the RQs and be compatible with ontological assumptions informing the study (in terms of the nature of what is being studied) and epistemological considerations in terms of what it is reasonable to expect to be able to know about that kind of research focus. A methodology should therefore be selected (see below) which is suitable to answer the RQ, taking into account the presumed ontology of what is being studied and the kind of knowledge considered viable for such a focus; and data collection and analysis techniques are then selected which are coherent with that methodology. Data is collected (another 'expansive' stage, see Fig. 57.1) and then analysed to produce findings/results (another phase of concentration and reduction, see Fig. 57.1), developing a logical case for making new knowledge claims.

57.6 Conceptualising the Research Project

Discussions of educational research often make references to such notions as the 'theoretical perspectives' and 'conceptual frameworks' supporting particular research studies. The way these terms are understood, and will be used, in the present chapter (as unfortunately different authors do not always use a common terminology – see the comments below about phenomenography) is represented in Fig. 57.2. As well as 'theoretical perspective' and 'conceptual framework', this figure also includes three other key terms: 'research questions' (as discussed above), 'research design' and 'methodology'.

RQs are the specific questions that a research study is intended to address. These may take the form of a formal hypothesis, but in educational studies, they may instead be much more open ended, and the degree of openness will often depend upon the current state of knowledge in the topic area (as will be discussed further below).

The RQs for a particular study derive from a conceptualisation of the topic area that sets out what is already known and what is not yet known and might be worth finding out. The wording here, 'what is already known', is not intended to suggest absolute knowledge, but rather the set of knowledge claims currently considered robustly supported, and so suitable for taking as a starting point for further research. This conceptualisation, the 'conceptual framework' of a study, is often formalised in the literature review of a research report. The RQs are addressed through a 'research design' that sets out how the required data are to be collected, and how they will be analysed so as to answer the RQ. The essential logic of a research 'design' is such that it should in principle be prepared ahead of the empirical work taking place, and indeed doctoral students are commonly expected to have their research designs scrutinised and approved before commencing their 'fieldwork'. However, as in the natural sciences, research may involve false starts and

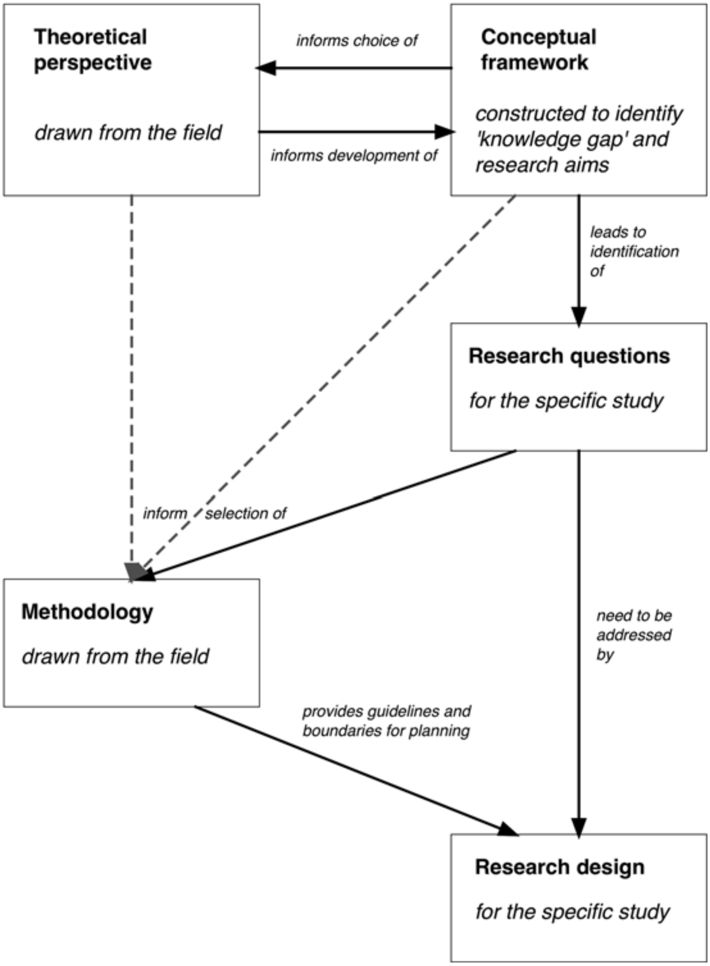

Fig. 57.2 Some key terms used to describe educational research

unproductive 'cul-de-sacs', and the design reported in published reports (and theses submitted for examination) may well – as in the natural sciences (Medawar 1963/1990) – be a rational reconstruction, in the light of experience, of what eventually 'worked'.

In some forms of educational research, the research design might be synonymous with 'experimental design', but, as is discussed below, many educational research designs are not based on experimental methods. Moreover, some research designs are 'emergent' which means that only the initial stages of data collection are firmly established before the research begins, as further detail of the research design will be informed by ongoing data collection. This is a somewhat different issue to the previous point regarding false starts (where a pre-planned approach that it was anticipated would be suitable for answering RQ is later found to be unproductive), as with an emergent design it is recognised in advance that an iterative process will be needed to refine the design.

In a grounded theory study, for example, it would be inappropriate and counterproductive to fully specify the data collection for the entire study in advance (as will be seen from the description later in the chapter, that would undermine the logic of the methodology), whereas in an experiment, it is important to specify data collection and analysis carefully in advance – although the specification that is reported in a formal account may well have been preceded by earlier versions that were abandoned as the research was developed.

Not reporting the outcome of experimental studies because those outcomes are not welcome is unethical, but not reporting studies because they are judged to have methodological failures that undermine the credibility of the results is quite appropriate (and indeed journal referees may well judge studies in these terms even when the researchers consider the procedures employed adequate). Ultimately, it is the researcher's judgement (and so their professional integrity) that has to be relied upon to discriminate between results that go unreported because they are not robustly supported and results that are robust but do not support conclusions the researcher hoped to draw. This issue is familiar enough from work in the natural sciences (Polanyi 1962/1969).

The process of shifting from a conceptual framework to specific RQ and then to a research design is clearly familiar from the natural sciences, although there it is more likely (although not always the case) that research design will imply experimental design and that research designs will be specified in detail (precisely which data to collect, precisely how it will be analysed) before any data collection begins. The argument offered in this chapter is that there are necessary (essential) differences between educational research and research in the natural sciences; but that this need not exclude research in science education from being considered 'scientific'. In particular, the process of designing and justifying research is likely in science education, more (or more often) than natural science, to require *explicit* consideration of ontological, axiological and epistemological considerations.

57.6.1 Theoretical Perspectives

Educational phenomena, teaching and learning and the social institutions intended to support teaching, can (as Shulman 1986 recognised) be very complex, and there are often alternative ways of approaching the conceptualisation of a particular research focus (such as student learning about some science topic). Discussions of educational research often make references to the 'theoretical perspective' informing a study, as something other than the 'conceptual framework' underpinning the study.

Theoretical perspectives can be thought of as well-developed theoretical positions about some aspects of a social or educational phenomenon that can act as starting points for making sense of research topics. An important point is that in science education, there is no 1:1 correspondence between theoretical perspective and

By contrast, the oxygen theory competed with the phlogiston theory to occupy the same explanatory space – of why combustion sometimes (but not always) occurs.

Similarly, descent with modification through natural selection (Darwin 1859/1968), and the notion that organisms are members of a species because of some essence (Mayr 1987) competed (and indeed for some still compete) in the 'explanatory space' for explaining how living things on earth appear to fit into a number of specific types that (although very large) is tiny compared with the number of individual organisms on earth. Theodosius Dobzhansky (1935, p. 345) enquired whether the notion of a species was 'a purely artificial device employed for making the bewildering diversity of living beings intelligible, or corresponds to something tangible in the outside world…[that is, is] the species a part of the 'order of nature', or a part of the order-loving mind?' Indeed, it has been argued that the tendency to retain elements of essentialism long after the general tenets of Darwinian evolution were widely accepted has been a major problem in biology (Hull 1965), amounting to the kind of obstacle to scientific progress discussed by Bachelard (1940/1968).

These examples from the natural sciences give some sense of how theoretical perspectives might be drawn upon in particular research contexts. At first sight, a difference between research in the natural sciences and research in science education is that in education it may not always be so clear whether alternative theoretical perspectives are competing or potentially complementary. This difference reflects the complexity of educational phenomena (discussed further below) and is brought into focus because of the use above of historical examples from the natural science (combustion, particle theory, the origin of species) where we are judging the issue with the benefit of many decades of 'hindsight'.

A wide range of theoretical perspectives have been drawn upon in research in science education, but some illustrative examples would be the following:

Exploring college students' thinking related to the concept of field drawing upon a particular theoretical perspective of the main types of mental representations people use (Greca and Moreira 1997)

Exploring teaching and learning of cell biology in upper secondary school and drawing upon a theoretical perspective based on general system theory (Verhoeff et al. 2008)

Exploring the value of a sociocultural theoretical perspective in thinking about the learning that can occur when people visit science and technology centres (Davidsson and Jakobsson 2008)

57.7 Competing Theoretical Perspectives in Science Education

Space here only allows limited exemplification, but an example of where different theoretical perspectives have competed in science education concerns research into student thinking, understanding and learning in science. Two examples here concern flavours of 'personal constructivism' and the relationship between personal constructivism and sociocultural perspectives on learning.

A very influential theoretical perspective from developmental psychology that informed work in science education was that due to Jean Piaget and his ‘genetic epistemology’ (Piaget 1970/1972). Within that programme of work, Piaget developed a stage theory of cognitive development which saw particular domain general structures of thought as associated with different developmental stages and which put limits on the kind of learning possible for students at each stage (Piaget 1929/1973). Although details of the Piagetian scheme, and how it is understood to relate to education, have faced criticism (Donaldson 1978; Sutherland 1992), this has been a very influential perspective in science education (Bliss 1993, 1995). In particular, Piaget’s work with its focus on structures posited in mind (Gardner 1973) contrasted with work informed by the highly influential behaviourist school (largely in the United States) that had eschewed explanations relying upon non-observable constructs such as states of mind (Watson 1924/1998, 1967).

However, in the 1970s, an alternative perspective was developed in science education that focused less on general structures of thought (the complexity of thinking available to learners) and more on their particular meaning making in different scientific topics, leading eventually to an extensive research effort (Driver et al. 1994; Duit 2009). This research explored students’ own ways of thinking and talking about various natural phenomena and scientific topics, such as force, plant nutrition and heat. The aim here was less to characterise student thinking at particular levels, but to allow teachers to be aware of typical conceptions students brought to (and/or took away from) lessons, and to think about how to support students in developing understanding of the scientific models that were reflected in the school or college curriculum. This work was sometimes labelled as the alternative conceptions movement (ACM).

Both of these perspectives can be understood to be personal constructivist approaches, focused on how the individual comes to iteratively build up personal knowledge in the form of internal representations of the world (as directly experienced and as heard about second hand), but with rather different foci: one domain general (so learning in any topic is constrained by the general stage of development) and one very much on a topic-by-topic basis (where familiarity with a particular domain can lead to areas of relative expertise).

These two perspectives can certainly be seen to have competed for research attention and resources, although arguably they did not compete for the same explanatory space as they focused primarily on rather different aspects of science learning. That the ACM came to dominance within science education – although an important strand of research to inform teaching from the Piagetian perspective continued (Adey 1999) – probably said less about the perceived *validity* of the Piagetian perspective than the greater perceived *fruitfulness* of the ACM for actually informing teaching. It might also be tentatively suggested that the ACM was attractive to many of those setting out on research in science education because the terminology of early work (often conceptualised as being about identifying misconceptions) was more accessible than the rather specialised and perhaps seemingly esoteric language that had been developed within the Piagetian programme. That is not to suggest that the ACM was under-theorised, as that was not so (Driver and Erickson 1983; Gilbert and Watts 1983; Osborne and Wittrock 1985). However, as a research programme developed from within education (rather than the developmental psychology base of the Piagetian work), there was always a strong impetus to report work in terms that would make sense to classroom teachers.

More recently, much discussion and some contention in science education has been focused around the question of whether the adoption of a social constructivist perspective (Roth and Tobin 2006; Smardon 2009) should be seen as complementary to, or a potential replacement for, a personal constructivist perspective. That is, does the acknowledgement of the importance of social interaction in learning (directly through dialogue or indirectly through institutions and cultural artefacts) imply that considering learning as the personal sense making of individuals in order to construct personal knowledge in the form of mental models associated with the minds of individuals (and represented in the physical substrate of that individual's brain) is invalid (or at least, unproductive)? One view would be that the personal constructivist perspective adopts notions of knowing and knowledge that are no longer viable in terms of what is commonly claimed about how learning needs to be understood as socially situated, and how knowledge-in-action depends upon social context (Hennessy 1993).

However, from within the personal constructivist perspective, it can be argued that learning is a very complex phenomenon and that a sensible simplification for many purposes is to understand learning as due to processes that occur within the cognitive system of an individual learner who perceives their environment (in which other people and the signs of culture may be highly salient and relevant to learning); constructs internal models of it, and then acts according to the perceived reality provided by those models (acts that include making public representations of personal knowledge that can be perceived by others); and, where it seems appropriate, adjusts the internal models as indicated by feedback from the environment (including the public reactions of others to that behaviour). It is possible to adopt a more synthetic 'complementary' view of personal and social constructivism as useful perspectives that can both contribute to progressing science education (Taber 2009b): but this is by no means a consensus view in the community.[1]

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[1] Just as there is a vast literature drawing upon and adopting (labels if not always principles) of constructivism, there has been a range of criticisms of constructivist work in science education. These include criticisms of constructivist approaches that seem to support relativist stances on scientific knowledge (Coll and Taylor 2001; Cromer 1997; Matthews 1993, 1994/2014; Scerri 2003), suggestions that constructivist teaching approaches undermine traditional ecological knowledge in indigenous communities (Bowers 2007), the theoretical basis of constructivism in education (Matthews 2002), the level of empirical support for knowledge claims (Claxton 1993; Kuiper 1994; Solomon 1992), inappropriate focus on individuals (Coll and Taylor 2001; Solomon 1987, 1993b), limited linkage between result findings and implications for teaching (Harlen 1999; Johnstone 2000; Millar 1989; Solomon 1993a), associations with unstructured 'discovery' learning approaches (Cromer 1997; Matthews 2002) and diversion of resources from more productive areas of research (Johnstone 2000; Solomon 1994). An account of these criticisms and possible rebuttals is offered elsewhere (Taber 2009b). Some of these issues reflect a wider debate in education about the nature and relative merits of constructivist and enquiry-based teaching compared with other pedagogies – especially what has been labelled as 'direct instruction' (Kirschner et al. 2006; Klahr 2010; Taber 2010a, b; Tobias and Duffy 2009).

57.8 Selecting a Methodology for a Study

The term ‘methodology’ when used to describe research in education – or the social sciences more widely – is distinguished from ‘methods’, which generally means the specific ‘techniques’ used to collect and analyse data. Methodologies are considered to be broader: to be principled approaches to undertaking research that can provide a framework for selecting particular component techniques. A simple analogy here is that methodology refers to an overall strategy to achieve research aims, within which specific tactics (techniques) may be employed to meet particular subgoals (Taber 2007).

Although one might refer to the specific methodology used in a particular study, methodologies tend to be considered as general-purpose approaches that can be selected according to the nature of the RQ being addressed (as suggested by the analogy with pedagogy and pedagogies above). One common methodology would be the experiment, but educational research commonly also draws on a range of other methodologies such as survey, case study, ethnography and grounded theory. It is worth reflecting briefly on the core characteristics of these common methodologies.

Experiment: The experimental ‘method’ is taken from work in the natural sciences and is used to test a hypothesis by controlling variables to compare two sets of conditions that differ in one accord. In practice, true experiments are seldom possible in education, for reasons discussed later in this chapter.

Survey: A survey is used to find out about the level of association of one type of element with a different type of element. So, for example, a survey could be used to find how many fume cupboards school science laboratories are typically equipped with (i.e. reporting the proportion of such laboratories having no fume cupboard, one fume cupboard, etc.). Commonly surveys are used to seek self-report information from people regarding such matters as their attitudes or behaviours. Surveys may be used to test hypotheses by comparing responses to different survey items – e.g. one could test the hypothesis that a higher proportion of male science teachers than female science teachers expect to be promoted to head of department.

Surveys may be applied within limited populations (e.g. the students in one school), but are commonly used in relation to larger populations (e.g. secondary chemistry teachers in a national context) using sampling techniques and inferential statistics to make inferences about the populations sampled. A survey that all, or nearly all, science teachers responded to could tell us whether or not a higher proportion of male science teachers than female science teachers expect to be promoted to head of department; but in practice a representative sample of modest size is likely to be sought from which inferences can be drawn about the broader population.

Case study is a methodology used to explore a particular instance in detail (Stake 2000; Yin 2003). The instance has to be identifiable as having clear boundaries and could be a lesson, the teaching of a scheme of work in a school department, assessment procedures in a university teaching department, a group visit to a museum by one class of students, etc. For example, Duit and colleagues (Duit et al. 1998) report a classroom episode where one group of students undertakes a discussion task relating to the magnetic pendulum. The authors of the report provide extensive context for making sense of the case in terms of the classroom and curriculum setting of the episode.

Although case study looks at an identifiable instance, it is normally naturalistic, exploring the case in its usual context, rather than attempting to set up a clinical setting – which would often not be viable even if considered useful, as often the case is embedded in its natural context in ways that influence its characteristics (so moving a teacher and a class from their normal setting to a special research classroom in a university, for example, is likely to change behaviours that would be exhibited in the 'natural' setting).

Sometimes (instrumental) cases are chosen because they are considered reasonably typical of a class of instances, where the complexity of what is being studied suggests that more can be learnt by detailed exploration of an instant than surveying a representative sample. Other (intrinsic) cases may be selected because they have been identified as special in some sense, and the researchers want to see if they can find out why: for example, why one teacher facilitates especially impressive learning outcomes.

Ethnography is an approach drawing upon anthropology, which attempts to make sense of a particular culture or group in its own terms, that is, to understand the meaning the individuals in that culture or group assign to certain rituals or cultural practices (Agar 2001; Hammersley and Atkinson 2007). Whilst ethnographies, that is, detailed accounts produced by ethnographic methodology, are relatively rare, if not excluded (Long 2011; Reiss 2000), in science education, studies which draw on ethnographic approaches and perspectives are quite common.

Grounded theory is a set of methods for developing theory using an inductive approach. Developed – or 'discovered' (Glaser and Strauss 1967) – in sociology, grounded theory is an approach which attempts to provide methods to assure scientific rigour when researchers attempt to understand social phenomena and existing conceptual frameworks are considered inadequate. Grounded theory relies on a number of core principles (Taber 2000), including emergent research designs that build upon 'theoretical sampling' (i.e. using the analysis of initial data to inform decisions about the next steps in data collection), 'constant comparison' (an iterative approach to analysis that requires repeated revising of data coding intended to ensure analysis that provides best fit to all the data) and 'theoretical saturation' (i.e. only ceasing data collection when further data adds nothing substantive to the theory being developed).

As this suggests, the complete grounded theory methodology is very demanding and is only viable when researchers are not under strict time pressures to complete a study. Despite this, grounded theory is commonly cited as a referent in educational studies, although often in practice such studies adopt the constant comparison method without substantive theoretical sampling or reaching theoretical saturation.

57.8.1 Other Candidates for Methodology

Sometimes *phenomenography* is considered a distinct methodology, although it is alternatively considered rather to be a particular perspective (e.g. Koballa et al. 2000), an analytical framework (Ebenezer and Erickson 1996) or even a field of enquiry (Marton 1981). Phenomenography seeks to describe, explore and characterise people's experiences.

Approaches such as lesson study and design research may also be considered as methodologies. In lesson study (Allen et al. 2004), an approach to curriculum development that has been especially popular in Japan, a group of teachers work together to plan a lesson, which is then taught by one of the group and observed by others. This allows the lesson plan to be revised, before another member of the group teaches the revised lesson, allowing a further 'trial' and opportunity for further refinement.

Whilst such approaches might seem to be more about 'development' than 'pure' research, if educational research is intended to improve teaching, then such approaches certainly cannot be excluded from consideration. Some commentators on educational research see a major distinction between 'pure' and 'applied' research (Springer 2010), but arguably all 'educational' research (as opposed to, say, psychological research into learning) should potentially have at least distal implications for informing educational activity, and the pure/applied division is not an especially helpful distinction. Arguably this presents a difference between research in science and research in education: perhaps because work exploring educational phenomena that could be considered as 'pure' would be likely to be considered not as educational research but as research in another area such as educational psychology or sociology undertaken within educational contexts. Certainly if we adopt the steer offered by Pring (2000, p. 27), then educational research is always in principle 'applied' research.

Rather, a more significant issue raised here is the role and nature of theory in research and the extent to which curriculum development and lesson design need to be seen as idiographic activities specific to the particular subject matter, curriculum setting, institution and cultural contexts, of teaching and learning. This is an issue where the science education community has not reached a strong consensus (Kortland and Klaassen 2010; Tiberghien 2012). There is an argument that the complexity of teaching and learning is such that iterative processes (such as that used in lesson study) are needed within teaching and should be institutionalised within the profession to make it a 'design science' (Laurillard 2012).

This leads to consider another methodology that is often cited in educational research, i.e. '*action research*' (McNiff 1992). Like many of the descriptors used in discussing education research, action research is understood differently by different authors, but usually means research that is carried out by practitioners to address a problem or issues in their own practice. A key feature of action research is its cyclic nature, with the practitioner-researcher implementing and evaluating an innovation intended to address the concern and then modifying the innovation as indicated by the evaluation. There is then a similarity between the action research cycle and the learning cycle (Marek 2009). The focus of action research is meant to be the improvement of the practical situation, rather than the development of generalisable theoretical knowledge, and so action research often lacks detailed documentation and formal reporting.

That said, published studies are sometimes said to be examples of action research, although generally to be considered worthy of publication, such studies are expected to demonstrate both a level of documentation, and a robustness of argument for knowledge claims, outside the typical characterisation of action research. That is, the logic of action research is that at the end of each cycle, decisions about the next cycle of action are based upon judgements 'on the balance of probability' rather than waiting to accumulate sufficient evidence to support formal knowledge claims that would be robust enough for presentation in an academic research journal.

Arguably, action research is less a methodology as such than a mode of research that is context directed, where the focus is on improving practice within a specific context, rather than developing abstract, generalisable, theoretical knowledge. This is in contrast to academic research that is theory directed, but which might collect data in a limited specific context as a methodological choice (e.g., if a case study seems most appropriate to answer RQ). From this perspective, true (context-directed) action research is unlikely to provide the basis for academic research reports, but there is no 'in principle' reason why *practitioner* research cannot contribute to the academic research literature as long as it is suitably theory directed and not exclusively concerned with addressing an immediate issue embedded within the practice context. Such practitioner research would need to apply suitable methodology to support theory-directed work (i.e. action research per se would not be such a methodology), but could still be initially motivated by a local problem or issue and may well contribute to improving practice, as well as offering a more generalisable contribution. There is therefore a good reason to avoid conflating action research with practitioner research more generally.

The methodologies described here do not exhaust the methodologies claimed in research papers. As well as variations, refined and hybrid versions of the above methodologies, there are also references to quite different methodologies. However, what counts as a distinct methodology is open to debate. It could be argued, for example, that so-called feminist methodologies, such as the feminist ethnography used in a paper reported in *Science Education* (Basu 2008), are conflating a methodology (in this case ethnography) with a theoretical perspective (here, feminism) that is informing both the choice of that methodology and how research is designed based on that strategy (cf. Fig. 57.2). A counter argument would be that the more specific feminist methodology is distinct because it is informed by a particular value position (in this case 'the importance of research having benefit for research participants and their immediate community', p. 256). Whether or not feminist ethnography should be considered a distinct methodology in its own right, ultimately what is important is that methodological choices are carefully explained and justified, and as long as that is so, readers can draw their own conclusions about the worth of knowledge claims made, and the particular labels used as descriptors are secondary.

However, this example raises the important point that methodological decisions in educational research are informed by axiological as well as ontological and epistemological considerations.

57.9 Ethical Considerations and Their Methodological Consequences

All researchers should be informed by professional standards of ethics. In the natural sciences, a focus on research ethics often concerns such issues as not inventing data, not selecting results for reporting based on their level of agreement with preferred ideas and giving full acknowledgement to the work of others. These considerations also apply in educational research, of course, but there are additional ethical complications in educational work that do not tend to arise in most research in natural science. Often these issues are significant enough that methodological considerations may need to be compromised because of the ethical imperative.

57.9.1 The Good

Researchers tend to feel that research is inherently a good thing because it produces knowledge, which allows us a better understanding of some aspect of the world, and so can inform our choices. Even in the natural sciences, such a view might be challenged. Science provided knowledge to allow the development of explosives used in war as well as in engineering applications, poisons used in Nazi gas chambers and the atomic bombs dropped on Hiroshima and Nagasaki. If such applications are considered inherently evil (and few would dispute that at least in the case of the gas chambers used as instruments of genocide), then questions may be raised about the wisdom of the science that provided the technology. However, there is a common argument that knowledge in itself cannot be evil, as it can only inform human actions, where there is a moral choice to be made in how to apply such knowledge.

57.9.2 Costs and Benefits of Research

In areas such as medical science, there may be questions about the costs of the knowledge produced by research. Sometimes new treatments and procedures do more harm than good (as was the case with the use of thalidomide, which led to thousands of serious birth defects): but the medical profession is bound by an imperative to do no harm and so puts in place various safeguards to avoid harming participants in studies. Sometimes there is a recognised substantial risk, and a participant may choose to take that risk in the hope of a possible benefit. In such a situation the notion of informed consent becomes very important: that the person agrees to take the risk based on an understanding of the available knowledge about possible risks and likely benefits of participation. Sometimes participation is altruistic in the sense that the participant may be aware that there is likely to be minimal benefit personally, but that knowledge obtained may contribute to developing treatments to benefit hypothetical others at some future time.

57.9.3 Informed Consent

The medical research scenario offers a strong parallel to the situation regarding much educational research. Educational research may be carried out primarily to develop theories that might be applicable at some point in the future, and such research may potentially inconvenience teachers, learners and others who are asked to contribute through their participation now. We might hope that people would welcome a chance to contribute to the development of educational knowledge through participation in studies, but a researcher cannot require or expect this. Therefore informed consent must be obtained from participants, and the wishes of those potential participants who decline involvement must be respected, regardless of the basis of their decisions, even if this weakens or undermines a research design – such as an experimental design.

There are clearly complications with obtaining informed consent that relate to the ability of – especially young – children to understand what they are being asked to give consent to; regarding when parents as well as learners need to give consent; and about when teachers, acting in *loco parentis*, are able to give consent on behalf of students. Teachers, head teachers (or school principals), area education officers and government ministers may act as ‘gatekeepers’ who decide whether a proposed study can be carried out in particular classrooms and schools. They may well reject requests for research that is judged to have potential for undermining normal order and procedures.

Innovations that seem promising to researchers may be judged to make too heavy demands on potential participants; and even quite straightforward procedures such as administering simple questionnaires to classes may be considered unwelcome by busy teachers. This is often likely to lead to researchers compromising research design based on what might realistically be granted when permission is sought. Experimental designs that look to compare two different teaching and learning conditions can often apply inferential statistics, providing that the learners are randomly assigned to conditions. However, in practice, researchers are usually restricted to working with intact classes, where, at best, whole classes can be randomly assigned to treatments – a much weaker design. Indeed, sometimes the choice of the ‘treatment’ and ‘comparison’ groups depends upon which teacher is prepared to adopt some innovative practice, immediately suggesting that teacher characteristic may well be a confounding factor.

A particular issue that arises is that where some potential participants decline to be involved in a project, this may well bias any attempt at sampling. If a study seeks a representative sample and reasons for granting or declining consent link to the issues being researched, then the final sample may well be skewed.

57.9.4 Openness and Confidentiality

Another key issue that may lead to methodological compromises is the need to respect participants' desire for anonymity in research. Generally, it is considered appropriate to assure potential research participants that their data – and it has been argued that the data is *theirs* to gift to the researcher (Limerick et al. 1996) – will be kept confidential within the research team and that any reports will be written such that individuals (and often institutions) cannot be identified. This is more readily assured in some types of research than others. So reporting detailed case studies, where the expectation is to provide 'thick description' to support reader generalisation (i.e. where the reader makes a judgement about how well the reported context is similar to their own professional context), may be difficult without giving away information that would allow informants to be identified.

Indeed there are examples of research in the science education literature where the published details seem to make it very unlikely more than one person could match the description (see examples disucssed in Taber 2013). Sometimes it is suggested that it is appropriate for researchers to deliberately change some biographical or other details to assure anonymity of participants – but this clearly means providing a report which is known to be false in certain regards and puts the onus on the researchers to know what details can be changed without undermining the authenticity of the published account.

57.9.5 Member Checking and Rights to Withdraw

A further complication of respecting the rights of individuals involved in educational research is that it is often suggested that a participant should have the right to withdraw from a study *at any stage*: 'researchers must recognize the right of any participant to withdraw from the research for any or no reason, and at any time, and they must inform them of this right' (British Educational Research Association 2011, p. 6). This can clearly undermine research designs. In longitudinal studies, it is quite common to experience attrition as participants leave the study for various reasons, and this might modify the balance of participants sampled if decisions to continue participation or withdraw may be linked to issues being explored. To some extent, this might be accommodated by building-in redundancy through enrolling more participants than are required for what is considered likely to be a sufficient data set – but that may well require additional resources.

In an interview study, for example, it is normal to advise participants that they may stop the interview at any time or decline to answer any particular questions. If a sequence of interviews are planned, the participant is invited to continue their participation on each occasion, i.e. the researcher cannot expect them to abide by commitments perhaps made months before. It is commonly also suggested that whilst a study is in progress, participants should not only have the right to decline further participation at any point but also have the right to withdraw any data they have provided *earlier* in the study.

A related point concerns the right to comment on material written about a participant. In some forms of research, particularly interpretive studies claiming to report on the views, ideas and opinions of others, it is recommended that the participants should be invited to read, and comment on, any draft reports relating to their own cases – this is known as member checking. In itself this is as much a methodological as ethical safeguard, as it gives participants the chance to check the researchers' interpretations of their inputs are valid. Any feedback received from such 'member checking' should be treated as additional data that needs to be considered in drawing conclusions. Clearly at this point, there might be potential for a participant to request particular changes (if perhaps they feel their comments are not presented in a favourable light) and seek to withdraw their data from the study otherwise. This has potential to undermine the integrity of a study.

There are clearly circumstances where member checking has less value methodologically. One case would be where students' thinking is analysed in relation to canonical scientific thinking, where it is likely that a student holding an alternative conceptual framework may not be in a strong position to confirm or otherwise the worth of the analysis. In such research, there are techniques that can be adopted as part of interview procedures to ensure the validity of the interpretations being made by researchers during data collection (although it should be noted that further insight into students' thinking may emerge later during analysis): confirming responses by repeating or rephrasing questions; clarifying ideas by asking follow-up questions; paraphrasing what one believes to be the learner's argument, and seeking confirmation; returning to the same point in the same context later in the interview, to see if a consistent response is given by the learner; and approaching the same point through a different context later in the interview, to see if the learner gives consistent responses in the different contexts (Taber 1993). Member checking may also be of limited value in studies looking at shifts in participants' opinions, as participants may not retain a clear and accurate recollection of their earlier stances once their thinking has moved on.

57.9.6 Particular Challenges of Teacher Research

Ethical issues may become especially problematic for teachers and lecturers undertaking research with their own classes (and colleagues). There are a number of complications here compared with research carried out by 'external' researchers.

For one thing, the usual ‘gatekeepers’ who normally need to approve a study before researchers approach students about being potential participants can be bypassed. A second issue concerns obtaining informed consent, as students could feel that they are obliged to help their teacher who will often have a role in writing reports on them or grading their work (Taber 2002). Although the teacher may not seek coercion, safeguards are needed to assure students that participation is entirely voluntary and that nonparticipation carries no penalty in regard of their study. Both of these issues can somewhat be countered by recruiting a suitable senior colleague to act as a nominated person to check on the procedures being employed and informing students that they may refer any concerns to that person.

A difficult issue is to decide when research goes beyond normal teaching practice. The fully professional teacher is expected to be research informed and able to develop their teaching through classroom research (Taber 2013). Teachers are expected to innovate and to collect data so that they know how effective their teaching is. An innovative teacher, trying out new ideas to improve their teaching and collecting classroom data to evaluate their work, would *not* expect to have to seek permission from the learners in the class (and/or their parents for younger learners) nor to offer opportunities for some class members to decline to be involved in any lesson activities based on innovative approaches. Yet, in effect, this kind of evidence-based teaching practice is a form of research. This is indeed an area where it may not be clear when classroom enquiry and innovation should be considered primarily research rather than just good teaching practice.

However, what is clear is that the science education research journals contain many examples of studies based upon data collected and analysed by teachers working with their own classes, where the impression given is that the purpose of data collection was research (rather than as a normal part of teaching) and where often there is no mention of how the research was presented to learners nor whether they were invited to contribute and given the choice to decline. That is, some of these studies are written as though the authors feel that they are entitled to set exercises to collect data without consideration of the way they are using their students as data sources. Perhaps the researchers in such studies did follow appropriate ethical procedures, but if so they did not feel the need to report they had done so.

Increasingly, journals are expecting authors to make a declaration on submitting studies to the effect that appropriate ethical guidelines have been followed: although this relies on the researchers having a good understanding of the issues involved. It is suggested here that there are useful criteria that can be used to decide when evaluations of teaching innovation, or other examples of teacher research, should be considered to need informed consent from students (see Table 57.1). These concern the nature of the activity used to collect data, the purpose of the data collection and the intended use of the results (Taber 2013).

So it is suggested that researchers should (i) seek explicit consent from students they would like to be involved in studies and (ii) acknowledge that informed consent was given in research reports, when the research (a) requires input from students outside of the normal classroom/curriculum schedule and/or (b) is ‘theory directed’ (i.e. looks to answer general questions, where learners involved stand for learners

Table 57.1 Determining when teacher research requires informed consent from learners

	Teacher research should be considered a part of normal classroom practice when	Teacher research requires informed consent from learners when
Activity	It involves normal teaching and learning (including assessment) activities carried out within normal curriculum time	It goes beyond the normal range of teaching and learning (including assessment) activities and/or occurs outside of normal scheduled curriculum time
Purpose	It is intended to help understand better an aspect of the professional context or solve problems arising within that context, i.e. knowledge is sought to inform educational practice in the institutional setting that will benefit the learners involved in the research	It is intended to answer general theoretical questions and support the development of abstract knowledge (i.e. the students' concerned are just a convenient sample considered to represent a broader population of learners)
Dissemination	Research results will inform the teacher-researcher and may be shared will departmental or other colleagues working in the same institutional setting	It is intended that research results will be submitted for publication or disseminated through websites, conferences, networks, etc. (N.b. this would apply to research undertaken for an academic award)

generally) rather than context directed (where the research is aimed at specific issues relating to the teaching and learning in the particular research context) and/or (c) is intended for reporting and dissemination beyond the institutional context where the research is undertaken.

Following these guidelines will protect learners from being treated as research fodder and will protect researchers from suspicion of unethical practice.

57.10 Selecting Techniques in Educational Research

There is not a simple correspondence between methodology and particular techniques, but there are some clear patterns. Experiments require some form of quantification. Surveys tend to involve the use of questionnaires and/or structured observations. Case studies tend to use a range of techniques, commonly including interviews, observation and document analysis.

Interviews can be used as data collection techniques in a range of methodologies, but the *type of* interview used may change from one methodology to another (and this is also true of observational techniques). So an interview in a study employing survey methodology is likely to employ a highly structured schedule of questions (in effect, an oral questionnaire) which the interviewer is not supposed to vary (i.e. to ensure comparability between respondents), whereas in an ethnographic study, interviewing is likely to be based around a much more flexible interview schedule that allows the interviewer to probe for the participants' understandings and perceptions and to use the interactive nature of conversation (Bruner 1987) as a means to check and refine the researcher's interpretations of what they are being told. In effect these types of interview are rather *different techniques*, informed by rather different assumptions about what is methodologically appropriate in a particular study (see below). In the survey interview, it is assumed that (in principle) the interviewer could be replaced by another trained interviewer without influencing the responses of participants. Such objectivity may be more difficult to achieve in an ethnographic study where the sensitivity of the researcher to nuances in responses is much more significant.

A research design should include the ways in which data will be analysed, as well as how they will be collected, and again particular ways of analysing data are linked with particular methodologies. So, for example, formal hypotheses tested through experimental or survey approaches require the deductive use of quantitative methods applying inferential statistics, whereas grounded theory employs the 'constant comparison' method of ensuring theory is developed from data by an inductive approach. In some methodologies, it is expected that triangulation (Oancea 2005) from different data sources, or even different data collection techniques, is used to ensure the 'trustworthiness' of research (Guba and Lincoln 2005). However, this is not considered necessary when research techniques are considered to unambiguously access ontologically clear research foci (as in a well-designed experiment).

Whilst Fig. 57.2 does not show any direct link from the theoretical perspective (or the conceptual framework) to a research design, it is intended to imply that an indirect influence occurs through the RQ. The formulation of RQ involves selecting terms and phrasing that reflect, and imply, particular meanings that have been developed through the formation of the conceptual framework, informed by the theoretical perspective identified as the starting point for building an understanding of a topic.

An interesting question is to what extent the process reflected in Fig. 57. 2 would be recognised as relevant to research in the natural sciences. It is argued in this chapter that *in principle* the same kinds of consideration that apply in educational research also apply in research in the natural sciences, but much more can be taken taken-for-granted within 'normal science'.

57.11 Typologies of Educational Research Methodologies

A key analytical tool used in characterising educational research is a description of several levels at which the research can be described. Commonly three or four levels are posited that shift from a consideration of philosophical commitments underpinning the research to identification of particular techniques to collect and analyse data. For example, one commonly cited model is that used by Crotty (1998), who describes social research at four levels: (i) epistemology, (ii) theoretical perspective, (iii) methodology and (iv) methods. As one example within this scheme, *a questionnaire* (method, i.e. technique) might be used to carry out *a survey* (methodology) from a *positivistic* theoretical perspective drawing upon *objectivist* epistemology.

This is only one of the schemes recommended in textbooks on social and educational research, because it is very difficult to find a common analytical framework that readily fits all different forms of research in education. A somewhat more simplistic model (Taber 2007, 2013) posits three basic levels of analysis understood as philosophical (the level commonly called paradigm in the social sciences), strategic (methodology) and tactical (techniques).

Crotty discusses three epistemologies: objectivism, constructionism and subjectivism – depending on whether meaning is considered to be *inherent in* an object, to *arise from interactions with* an object or to be *imposed upon* an object by a subject. Often in accounts of research such as Crotty's, the impression is given to novice researchers that they are expected to adopt one of these epistemological perspectives as a way of understanding the world. Yet this would seem to imply seeing the world as comprised of objects that at some fundamental level are of the same basic nature, at least in terms of what we might aspire to know about them. Such a perspective may be contrasted with pragmatism (Biesta and Burbules 2003), which is unfortunately (and inappropriately) sometimes presented as having little time for philosophical issues, but rather simply looking for tools to do particular (research) jobs.

Neither the adoption of a blanket epistemology nor of a naive pragmatism offers a justifiable approach for educational researchers when considering methodologies to adopt for particular purposes. The position taken here is that the extent to which researchers can both (a) clarify the ontological status of foci of research; and (b) directly and unambiguously access the foci of research; varies considerably in educational work, and therefore the selection of epistemology must reflect the needs of a particular study. So, for example, it does not make sense to consider that the same assumptions will support research into the provision of Bunsen burners equipping school laboratories, student attitudes to practical work and teacher understandings of socioscientific issues.

57.11.1 Qualitative Versus Quantitative

In a book on research design, Creswell (1994) suggested that once a focus for a study was established, the next step was the choice of paradigm, and he presented two options: the quantitative (or positivist, experimental or empiricist) paradigm and the qualitative (or constructivist or naturalist) paradigm. According to Creswell, particular methodologies (or as he called them methods) were appropriate for each of these paradigms (Table 57.2).

The reference to paradigms here reflects the adoption of the term in the social sciences after the widespread influence of Thomas Kuhn's work (considered above).

Table 57.2 A typology of research methodologies, after Creswell

Quantitative methodologies	Qualitative methodologies
Experiments	Ethnographies
Surveys	Grounded theory
	Case study
	Phenomenological studies

The identification of a paradigm which is considered positivist, experimental or empiricist might seem to some to imply a more 'scientific' paradigm. However, in the present chapter, it is argued rather that a scientific approach involves a choice of methodology that is consistent with the aims of the particular study.

A major problem with the Creswell classification is the prominent use of the terms 'quantitative' and 'qualitative' as major labels, as these terms have come to be used in very different ways in educational research. One common way in which the terms quantitative research and qualitative research are understood is in terms of the type of data being collected and analysed. Certainly there is an important difference between quantitative *data*, which is suitable for certain types of analysis, and qualitative *data*, which needs to be treated with different analytical approaches.

However, even that distinction is not absolute, because there is a spectrum of approaches to the analysis of qualitative data (Robson 2002). So, for example, it may well be that interview transcripts, providing text (qualitative data), may be analysed by counting specific words or phrases to test some hypotheses (i.e. quantitative analysis). It is also common for qualitative data to be initially analysed using interpretive approaches (qualitative analysis), leading to the assignment of coding which then leads to counts of the frequencies of certain codes, which could be the basis of either descriptive statistics or, again, hypothesis testing.

However, in other studies, qualitative data may be treated in much more thematic and narrative ways, with no frequency counts or other quantification. So even when we restrict our focus to data, the quantitative-qualitative distinction is of limited value once we shift beyond the description of the data itself to its analysis. Moreover, if the focus is on the nature of the data itself, then it makes little sense to align methodologies such as case study and grounded theory, which may commonly employ both qualitative *and* quantitative data collection and analysis, under a qualitative paradigm as Creswell does.

Where the focus of qualitative and quantitative is sometimes on the type of data being analysed, the term quantitative research is also sometimes reserved for the use of hypothesis testing approaches, excluding studies that analyse quantitative data to offer purely descriptive statistics. Similarly, some authors limit the use of the term qualitative research to studies that admit the necessity of a subjective element (Piantanida and Garman 2009) and are based on an interpretative approach that does not claim objectivity in the normal scientific sense – because it is argued that some kinds of social phenomena can only be understood through the intersubjectivity formed through establishing researcher-participant rapport and that the kind of detached observer who could claim objectivity would not be able to access suitable data for the study. There are clearly many studies based on the collection and analysis of qualitative data that are not 'qualitative' research in *that* sense.

Table 57.3 Two traditions or paradigms for educational research after Gilbert and Watts (1983, p. 64)

Tradition	*Erklären* tradition: explanation is the goal	*Verstehen* tradition: understanding is the goal
Outlook	Realist – adopting an empirical-inductivist view of knowledge	Relativist – influenced by post-inductivist views of knowledge
Target	Seeking causal mechanisms	Seeking understanding as shown by the individual actors (without the overt pursuit of generalisations)
Characteristics	'Nomothetic': general laws are sought	'Idiographic': relates to the study of individuals
	'Quantitative': suitable sections of a general population are enquired into	'Qualitative': seeks to enquire into phenomena without undue regard to their typicality
	'Prescriptive': outcomes of enquiry are intended to determine future actions	'Descriptive': no overt intention of determining future actions
Approach to phenomena	Reductionist – phenomena are subdivided and the divisions selectively paid attention to	Holistic – phenomena are studied in their entirety
Methodological approaches	'Experimental': controlled situations	'Naturalistic': naturally occurring situations

57.11.2 Two Paradigms for Educational Research?

It seems clear that when used as primary descriptors without further qualification, the terms qualitative and quantitative can be ambiguous and so unhelpful. Gilbert and Watts (1983) also used the descriptors 'quantitative' and 'qualitative', inter alia, when they described two common traditions or paradigms for research that could be employed in science education. However, Gilbert and Watts offered explanations for their uses of the term, in the context of setting out two clusters of characteristics of these two traditions. Their two paradigm descriptions are summarised in Table 57.3, and several of their points will be reflected in the following treatment.

One aspect of the Gilbert and Watts scheme that needs comment is the notion of their 'paradigm 2' (*Verstehen* tradition) being a relativist one. For some commentators, any admission of relativism is seem as antiscientific, and indeed Scerri has attacked the prevalence of 'constructivist' thinking in science (and in particular chemistry) education because of its associations with relativism. Space does not allow this debate to be explored in detail here (see Scerri 2003, 2010, 2012; Taber 2006b, 2010c), except to note it is a rather different proposition to suggest (as a hypothetical example) (a) that the choice between (i) the ancient system of earth, fire, water, air and aether as elements and (ii) the modern periodic system as a basis for scientific progress is all a matter of cultural perspective (a kind of relativism difficult to justify scientifically) than it is to suggest (b) that it is important to investigate and respect learners' alternative conceptual frameworks because of their influence on the individual's *learning of* science.

As suggested above, the research focus on students' ideas in science derived from concerns with the common patterns of conceptual development and the difficulties of learning canonical science, rather than any suggestion that students' ideas offered a viable alternative basis for scientific progress. Indeed it has been noted that common alternative conceptions often share at least superficial similarities with historical scientific models and theories long abandoned (Piaget and Garcia 1989).

Often in education, we are concerned with exploring the personally constructed 'realities' (i.e. the reality as experienced) of individuals because personal sense making is at the heart of the learning process (Glasersfeld 1989). The decision to focus on such 'second-order' perspectives (Marton 1981), i.e. other people's construing of reality, *need not* imply abandoning a belief in an absolute external reality. This can be considered analogous to how the historian of science may use hermeneutic methods to understand how scientists of the past understood scientific concepts because of the value of knowledge of those personal conceptions to our understanding of the history of science, not because anyone is suggesting that such outdated ideas are as valid as current scientific thinking.

The extensive research into student understanding and thinking in science associated with 'constructivism'/the ACM was strongly informed by existing traditions of work which emphasised the importance of a person's existing ways of understanding the world as the basis for how they made sense of experience and so how that interpretation of experience informed their actions in the world (Taber 2009b). In particular, key constructivist thinkers in science (and mathematics) education were informed by the genetic epistemology (Piaget 1970/1972) of Jean Piaget (Driver and Easley 1978; Gilbert and Watts 1983; Glasersfeld 1989) and the personal construct theory (Kelly 1963) of George Kelly (Gilbert and Watts 1983; Pope and Gilbert 1983).

One significant distinction between research methodologies does closely resemble that suggested by Creswell, but is not best distinguished by the labels qualitative and quantitative. Rather, these two types of research are better characterised according to whether the research is intended to test out existing established theory through deductive methods or rather to better understand poorly theorised phenomena to aid the development of new theory (Biddle and Anderson 1986). Developing this idea suggests two clusters of characteristics of research studies, as shown in Fig. 57.3.

This perspective does not set out different methodologies as fundamentally concerned with different research enterprises, but rather reflects how in any area of scientific activity there has to initially be a period of exploring and categorising and 'making sense' of the phenomena of a field – what has been termed the 'natural history' phase (Driver and Erickson 1983) – that can lead to the kinds of theorising, and subsequently bold conjectures (Popper 1989), suitable for formal testing (see Table 57.4).

That much of educational research concerns the former, more exploratory, types of study may be partly related to the relative immaturity of educational research compared with the established natural sciences. However, there are also inherent features of education that channel much research towards the discovery pole. One of these features, noted above, concerns the inherent complexity of educational

Fig. 57.3 Two main types of research in education

Table 57.4 Exploratory and confirmatory research

Paradigmatic commitment	Application	Suitable methodologies
Exploratory	In areas where no clear theoretical picture has emerged, due to limited research or complexity of phenomena	Case study Grounded theory
Confirmatory	To test hypotheses drawn from established theory	Experiments Surveys

Table 57.5 Idiographic and nomothetic research

Paradigmatic commitment	Application	Suitable methodologies
Idiographic	To enquire into educational phenomena where understanding requires detailed engagement with specific instances in their naturalistic context	Case study (to explore individual learners, classes, teachers, etc.) Ethnography (to explore cultures of identifiable groups)
Nomothetic	To enquire into aspects of educational phenomena that may be described in terms of norms and general laws	Experiments Surveys

phenomena, which are often embedded in situations from which they cannot be readily be disembodied whilst retaining their integrity.

This complicates attempts to use experimental method, as there may be myriad potential confounding factors that may be difficult to identify, let alone manipulate to control conditions, or, failing that, to measure so as to attempt to allow for during data analysis. As suggested below, this has encouraged much educational research to be focused on understanding the individual case in depth (see Table 57.5), despite

Table 57.6 Objectivist and constructivist-interpretivist research

Paradigmatic commitment	Application	Suitable methodologies
Objectivist	When dealing with issues where there is consensus ontology (the nature and demarcation of what is being studied) and clear epistemology (agreed means of learning about objects of research)	Experiments Surveys
Constructivist-interpretivist	Where exploring phenomena that are socially constructed and culturally relative or nuanced mental phenomena that can only be communicated through dialogue	Grounded theory (for understanding the central issues in social phenomena and institutions) Case study (to allow detail exploration of an individual or group) Ethnography (to provide immersion in culture to identify emic (insider) perspectives)

the problem of generalising from the individual to the wider 'population' (of teachers, of lessons, of learners, etc.).

Another key issue concerns the nature of teaching and learning as human activities. As such, there is a limit to the extent they can be seen as the subjects of objective study, because humans make personal meaning of and from their experiences, and many of the things we wish to study relate to those meanings (see Table 57.6). So whilst we might be more 'objective' when exploring class size, or curriculum content, or even whether student examination responses match specified features of canonical target knowledge; if we are interested in how a learner understands a concept, or the values they bring to science learning, or their experiences of a new teaching approach, etc., then we need to use ('constructivist'/'interpretivist') methods that can engage with and explore how others make sense of the world.

The best, though highly imperfect, apparatus we have for exploring one person's meaning making is the interpretive (meaning making) facility of another human being who can develop rapport with that first person and engage with them in some form of dialogic conversation. This affordance in some kinds of research is also linked to a serious threat to validity for those attempting to set up experimental research (i.e. in nomothetic mode). The expectations of researchers, or teachers working with them, are readily transferred to learners, and teacher enthusiasm or cynicism about some innovative approach being evaluated in a teaching-learning context can influence learners' own expectations, which in turn influence their perceptions of the innovation and so influence the learning itself. One common type of study compares learning in two 'comparable' classes where teaching by an innovative ('progressive') approach is compared with teaching through a 'traditional' approach. This immediately creates problems for making a fair comparison whether the teaching is carried out by the same teacher (will they be as equally adept and enthusiastic in both conditions?) or different teachers (who inevitably will bring different skills, and knowledge to their teaching). Added to that, the learners themselves may well react to the novelty of the innovation purely in terms of it being something different from the norm (which may well be welcomed, but could for some learners be perceived as threatening).

However we go about *collecting* data about the ideas, feelings, opinions, attitudes, etc. of others, we can only meaningfully *analyse* that data through the interpretations of other humans. This is what some commentators mean by ‘qualitative’ research (see above): research that relies on the intersubjectivity between researcher and study participants.

Whilst at first sight instruments such as questionnaires seem to avoid this intersubjectivity by presenting statements to be ranked or rated, the items in such instruments are only going to have validity (as statements that are both meaningful to respondents and understood by them *in the sense intended* by the researchers) when derived from previous research which explores what ideas and language will be meaningful for those surveyed – previous research which will necessarily have involved in-depth dialogic approaches (cf. Treagust 1988). Here again, the type of research which would fit under the right hand fork in Fig. 57.3 relies upon earlier rather different work that would fit under the left-hand column.

57.11.3 Mixed Methods: A Third Paradigm, a Subsuming Paradigm or a Rejection of Paradigms?

In recent years, those preferring the notions of quantitative and qualitative paradigms have admitted a ‘new’ paradigm known as mixed methods research: that is, research that employs a combination of quantitative and qualitative features (Creswell 2009; Creswell and Plano Clark 2007; Johnson and Onwuegbuzie 2004). Clearly if we focus on data type, there is nothing of special interest about mixed methods, as studies using quantitative and qualitative data are not themselves novel. It is less clear how a single study could at the same time employ genuinely distinct approaches such that it was at the same time objectivist/positivistic and constructivist-interpretivist if we take the former to suggest a realist ontology and an epistemology which allows claims that research offers in some sense an objective, researcher-independent, account of that reality and if the latter means accepting that the kinds of knowledge about the research foci that are possible are necessarily constructed by human beings and relative to the interpretations of a particular knower (Symonds and Gorard 2008). Given this, the claim that there is a distinct research approach known as ‘mixed methods’ – depending whether it refers simply to data type or something methodologically more substantial – is either fair but of no great significance, or alternatively is important but problematic (Taber 2012a).

This cynicism regarding the *label* of mixed methods derives from seeing it sometimes used in practice to describe a study’s methodology simply because both quantitative and qualitative data are collected. In that situation the label is generally unhelpful as it *at best* stands in place of a more informative label for the methodology adopted and *at worse* substitutes for the choice of an actual substantive coherent methodology. That is, in practice we sometimes find the label 'mixed methods' stands in place of principled thinking about the nature of what is researched and how to best enquire into it.

However, 'mixed methods' has also been positioned as 'an approach to knowledge (theory and practice) that attempts to consider multiple viewpoints, perspectives, positions, and standpoints (always including the standpoints of qualitative and quantitative research)' (Johnson et al. 2007, p. 13). Here mixed methods research is defined as 'the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration' (p. 123). Clearly the discussion here is not restricted to types of data, as presumably the 'standpoints of qualitative and quantitative research' relate to ontological and epistemological issues (are we dealing with the kind of things that can be countered and/or measured?; are we enquiring into something that will require intersubjectivity as an 'instrument' to elicit data?).

The position taken in this chapter, developed further below, is that such choices cannot be established in the abstract, but need to be addressed in the context of particular studies. As a field, science education cannot be well served either by limiting data to be collected to quantitative or qualitative forms; and nor can it progress by committing to the 'standpoints of qualitative [or] quantitative research' independently of the particular questions being addressed. However, if adopting 'mixed methods' as a paradigm (Johnson and Onwuegbuzie 2004) for educational research is taken to mean that we include within our methodological repertoire a wide range of approaches, from which to select according to the need of particular studies, then this fits well with the stance adopted here. The term mixed methods is perhaps unfortunate, as this approach is less a matter of 'mixing' our methods, than of making principled choices of methodology on a case-by-case basis for each RQ we wish to address. Yet it is the very diversity of methodologies, and research techniques adopted within them, that makes this approach quite unlike the kind of 'paradigm' that Kuhn intended in characterising normal science.

57.12 The Logic of an Extraordinary 'Sort of Science': Science Education as an Aparadigmatic Scientific Field

It was suggested above that perhaps research in science education, and indeed educational research more generally, might fail to look like Kuhn's normal science in part because of the pre-paradigmatic (Gilbert and Watts 1983; Jevons 1973) nature of the field, in which case we might be reassured by Kuhn's acknowledgement that another sort of science will be found in immature fields. Alternatively, we might share Shulman's (1986) view that this is not a matter of immaturity but rather of the nature of what is being studied (e.g. social institutions and processes; often idiosyncratic personal meaning making) which makes science education unlikely to develop a clear paradigm in Kuhn's sense. That is, we might consider science education will remain 'aparadigmatic'.

The next section focuses on these key features of educational research, the complexity and diversity of the phenomena of education and the inherent complications of research with human participants. The argument here is that science education may be a relatively immature field, but that even as it matures it is unlikely to develop a structure that supports an array of relatively discrete sub-fields each with its own disciplinary matrix to support the induction of researchers into a kind of normal science. Rather, given the high level of interconnectedness between different foci of research, all of which should ultimately inform teaching, science education should aspire to be a different 'sort of science' to Kuhnian normal science.

57.12.1 The Ontological Diversity of Educational Phenomena

We have seen that (a) particular research methodologies (strategies) rest upon fundamental assumptions and may cease to make sense as research strategies when those assumptions do not apply; yet (b) this does not restrict the researcher to a limited range of the available methodological choices in any absolute sense. Research design in education then must always (explicitly) take account of ontological and epistemological issues which logically constrain what may be considered sensible methodologies to adopt for particular studies: and as the educational world does not comprise only of entities of one particular ontological status, the starting point for designing research can be quite different for different studies – even within a particular subfield of science education.

That is, there are things of interest to science education researchers that can be tightly defined, fairly objectively identified in the world and counted and measured. These types of things are open to forms of investigation (in particular, research which collects quantitative data to test hypotheses through inferential statistical techniques: experiments, surveys) that would not make sense when the 'objects' of research are instead clearly culturally relative, socially constructed entities. So methodological choices must relate to the nature of *what* one wishes to research (which will have been posited in developing the conceptual framework for the study, cf. Fig. 57.2). Consider the following potential starting points for educational RQ:

- What is the average secondary school science class size in different countries?
- Is teacher subject knowledge or extent of classroom experience more important for successful science teaching?
- How do 11-year-olds understand energy?
- What are 11-year-olds' perceptions of the difficulty of science lessons?
- What is it like to be the only young woman in an undergraduate physics class?

One immediate point to make is that all of these topics involve research into some kind of entity external to the researcher him or herself, so the commitment to undertake research would seem to clearly be an acknowledgement that there is external reality which can be considered the object of (or subject for!) study. This immediately excludes some extreme philosophical positions from usefully informing research. Indeed the commitment to undertake educational research would seem to require the adoption of some key aspects of what is sometimes considered the scientific worldview (Matthews 2009). In particular, embarking on any educational research project would seem to require at least tacit commitment to:

- The existence of some kind of external reality;
- Which has some form of permanence;
- And exhibits certain regularities;
- And which human beings are capable of learning more about.

The posing of particular RQ goes beyond this and sets out certain specific types of entities (schools, classes, teachers, 11-year-olds, understanding, lessons, etc.) as targets or foci of research. That is, even at this stage, certain ontological commitments are revealed. Sometimes these entities are linked to our theoretical perspectives, as when research seeks to investigate Piagetian developmental levels, students' mental models or their alternative conceptions.

Adopting a common epistemology meant to refer to all that we recognise in our world (Crotty 1998) would not seem a sensible starting point. One needs to start from ontology: schools, classes, teaching, understanding, perceptions, mental models, etc. may all be considered to *in some sense* exist in the world, but they are not the same kind of things, and consequently one's epistemological assumptions about them may justifiably differ. So a fairly crude positivistic stance might well be appropriate and effective in seeking to find out the average secondary school science class size in different national contexts, as it is likely to be possible to identify countries and secondary school science classes in ways most observers would find unobjectionable, and determining class size is in principle a simple counting task.

Yet 'successful science teaching' (for example) does not present itself so unproblematically as the subject of investigation: what counts as successful science teaching has shifted over time and is culturally relative, and even in a particular educational context, there will not always be agreement on the appropriate balance between different mooted aims of science teaching – let alone the most suitable indicators that might allow us to make comparisons. Still, even here, in principle we can envisage that researchers might be equipped with an observation schedule of some kind and sent to observe lessons to evaluate the success of science teaching.

Of course no matter how well the data collection and analysis was carried out in such a hypothetical observation study, a reader of the eventual research report would only give credence to the findings to the extent that they accepted the particular conception of 'successful science teaching' informing the design of the observation schedule and were satisfied that the instrument itself could provide valid indications of whether the observed teaching was indeed was indeed 'successful' in *those* terms.

Depending upon how 'successful teaching' is understood, it is entirely feasible that it could even be considered something that could be 'measured' based on quantifiable outcome measures (such as student grades or satisfaction ratings). Where successful teaching is seen simply as teaching that leads to high levels of student examination success, then coming to know where teaching is successful is relatively simple.

Yet, if instead, successful teaching is considered to be about inculcating attitudes and values, about developing relationships, and about supporting maturation, and an interactive process that necessarily involves modifying teaching objectives according to the goals, needs, motivations and personal situations of individual learners, *then* coming to identify and differentiate successful teaching is going to be more challenging, more complex and so inevitably less precise. As always the researcher's epistemology has to be informed by their particular ontological understanding. Where researchers do not agree on the nature of what they are researching (and so in effect are not researching 'the same thing'), they are unlikely to agree on how best to go about their work.

This potentially puts some areas of educational research well outside the type of 'normal science' that Kuhn (1996) characterised as the basis of most work in the natural sciences – adopting canonical definitions and instrumentation widely considered to give valid and reliable results when applied within accepted ranges of application. There is a good deal of creativity and ingenuity at work in the natural sciences, but usually applied within a fairly well-agreed understanding of the nature of what is being researched and the methods appropriate for the job. This is less often the case in educational research. Ziman (1968, p. 115) notes how an 'experienced professional scientist seldom comes into conflict with the referees of his [or her] papers…because…he [or she] has internalized the standards that the referee is trying to enforce, and has already anticipated most reasonable grounds for criticism'. However, in science education, few papers are published without significant revisions required by referees: the experienced professional science education academic may come into conflict with the referees of his or her papers much more regularly than they would wish. This does not reflect on the professionalism of science educators but on the lesser extent of shared commitments and standards for work of those writing and refereeing for particular journals.

57.12.2 Admitting the Subjective Element into Research

Similarly, the classic distinction between the object of research and the (nominally interchangeable) researcher that is an ideal of natural science is often inappropriate in educational research: so where in the natural sciences it might be reported in depersonalised terms that that a sample was ground in a pestle and mortar, in an educational research report, *we* might well report how *we* spoke to a group of students. Eliciting student understanding, for example, is likely to require some kind of co-(re)construction of meaning through interaction between researcher and learner; and when investigating pupils' perceptions of lessons, it is indeed appropriate to consider that meaning is imposed on their experiences by the students themselves rather than being inherent in the activities they take part in.

As suggested above, this does not mean giving up belief in an external reality, but, in this case part of that reality is the experiences of others, and these are not open to being measured or counted like class sizes. Indeed, the best we can hope for is to ask others to represent their (internal mental) experiences in the 'public space' we share (e.g. through talk, drawing, role-play, etc.) and then to look to make sense of these representations in terms of the mental frameworks we have developed through our own experiences in the world (Taber 2014). This type of research *requires* an interpretivist (i.e. subjectivist) approach that acknowledges the difficulties inherent in the task.

Of course as individuals all we ever really know are our own experiences in the world, and there is always something of a leap of faith involved in assuming we share understandings with others. Yet there are differences of degree. We would generally expect that training different observers to reach the same objective 'head count' when surveying class sizes is likely to be less problematic than expecting different interviewers to construct the same model of a learners' understanding of energy or to reach the same understanding of how a female student experiences being the only young woman in an undergraduate physics class.

In the case of understanding energy, we might reasonably expect that such factors as subject knowledge, teaching experience, interviewing experience and expertise and familiarity with prior research could all influence the process of the researcher constructing a model of a learner's understanding, and so the 'results' of the study. In the case of the only woman in the science class, we might consider that the gender of the interviewer could be influential: both in terms of the experiences that the researcher brings to the research as interpretive resources and possibly in terms of the extent to which the female student feels able (or willing) to access and express her experiences and feelings about them.

Such complications undermine the possibility of doing research on people's thinking and experiences that can be as objective as we expect when investigating the resistivity of an alloy or the rate of a chemical reaction. Research always depends on the interpretive resources we bring to the work, *even* in the natural sciences (Keller 1983; Sacks 1995), but in educational research there are many things we want to study where we are unable to eliminate subjectivity, because the interpretive resources relevant to the task (needed to understand another's understanding or to appreciate another's perceptions and experiences) are highly variable among potential researchers. Indeed, we might often expect that the most insightful work is likely to depend upon researchers who have very *particular* knowledge, understanding and experience: such that any objectivist notion that we can substitute another qualified researcher and expect the same result becomes highly questionable.

57.12.3 The Scientific Approach to Educational Research Is to Adopt a Meta-Methodology

The picture painted above is of a field that appropriately draws upon diverse methodologies *because* it deals with a range of different types of research foci, which vary both in how well they are understood and indeed how directly they might be known. The intrinsic variety of educational phenomena and the subsequent diversity in ontological status and epistemological commitments appropriate to particular studies suggest that a mature science education would still lack the kind of constrained disciplinary matrix Kuhn associated with normal science. So science education is not pre-paradigmatic because of its relative youth, but is aparadigmatic because of its need to make principled judgements about methodology in the context of each new research design. Some may refer to this as a mixed methods paradigm, but this seems to pervert the term paradigm to something quite incongruent with its original meaning of a pattern that one can follow to approach a certain kind of problem.

Rather, if we consider methodologies such as experiment, survey and case study as types of strategy that we select between, then science education needs to be informed by a meta-strategy, a meta-methodology that offers guidance on the selection process. We might consider Fig. 57.2 to represent the operation of this meta-strategy, and the principles outlined above – regarding how building a research design needs to be informed by an ontological and epistemological analysis of the basis for the enquiry – indicate the kind of guidance needed. Perhaps, we might see this as aspiring to working within a 'meta-paradigm', not looking to induct researchers into adopting turnkey solutions for well-defined problem areas but preparing them to confidently build research designs bespoke on a principled basis.

If we wish to consider science education as a scientific enterprise despite the need to abandon the aspiration of evolving a research paradigm for the field, we may need to look elsewhere for a demarcation criterion for what counts as science. Popper is well known for his prescription that science should proceed by a process of bold conjecture and seeking refutation (Popper 1934/1959, 1989), and this has been understood as offering such a demarcation criterion. However, in practice, it is well accepted that (i) there is no simple way to determine what counts as a falsification of the theory being tested (rather than, for example, of technical competence or some auxiliary theory of instrumentation) and (ii) in practice crucial experiments only become accepted as such in hindsight, whilst many apparent refutations are quarantined as simply anomalies to be put aside for the moment. However, an alternative perspective on the nature of scientific work, able to distinguish science from pseudoscience, was developed by Lakatos, in his 'methodology of scientific research programmes'.

57.13 Thinking of Research Within Scientific Research Programmes

As suggested above, Kuhn's ideas have been widely criticised although they remain highly influential. In particular, Karl Popper was very critical of the apparently relativist flavour of Kuhn's worked, and there was a high profile debate around aspects of Kuhn's thesis (Lakatos and Musgrove 1970). Popper rejected the 'myth' of the incommensurability between paradigms implied in Kuhn's original formulation of his work (Popper 1994). It was also argued that the account of mature sciences as each consisting of successions of individual paradigms only interrupted by occasional revolutions leading to paradigm shift was an over-generalisation (Machamer et al. 2000) and perhaps was less true in sciences other than physics.

In particular, Imre Lakatos argued that that whilst paradigm-like traditions existed in science and whilst individual scientists would tend to work within such traditions – and indeed often continue to work within them for extended periods of time – it was not unusual for several competing traditions to coexist over considerable periods within the same field of science (Lakatos 1970). Whereas in Kuhn's model this could only happen if one tradition was in the process of being supplanted by its revolutionary successor, for Lakatos it was quite possible for several alternative traditions to continue to be productive and successful in parallel. In Lakatos's terms, these would be considered as co-existing progressive research programmes.

57.13.1 Lakatos's Notion of Scientific Research Programmes

Lakatos's model of scientific research programmes is especially relevant to the theme of this chapter, as it offers a demarcation criterion for what can be considered a scientific tradition that can be applied well beyond the natural sciences. Lakatos's work can be considered to set out the nature of a research programme (RP) and to also offer the criteria upon which such a programme should be considered *scientific*.

A Lakatosian RP shares some features with a Kuhnian paradigm. Both are research traditions that involve an initial establishment providing the basis for considerable later development work, and both require those working within the tradition to make particular commitments. Lakatos (1970) described RP in terms of four key elements in particular that he called the hard core, the protective belt, and the positive and negative heuristics.

The heuristics give guidance on how to develop the RP. The hard core comprises of those key commitments (e.g. ontological commitments), set out at the establishment of the programme, which are essential to the nature of that programme, such that if abandoned the essence of the programme is undermined and in effect the programme has ceased. The protective belt comprises of auxiliary theories that build upon and develop what is established in the hard core, and the positive heuristic sets out how this component is developed (e.g. strategic and methodological aspects of the programme). The auxiliary theories act as 'refutable variants' of the programme in the sense that they are consistent with the hard core, but may be abandoned without risk to the programme as a whole.

Consider, as an example, how modern chemistry has made considerable progress since the establishment of a RP based around modern atomic theory. A core commitment there is that at a submicroscopic level matter can be understood to be quantised and to comprise of discrete entities, particles (or perhaps better, quanticles) which can be considered to have specific properties such that chemical behaviour as observed in the laboratory can be explained by models at the submicroscopic level. Few chemists today will direct research at testing hypotheses that are in direct contradiction with those commitments (i.e. the negative heuristic suggests such work would be counterproductive given the core commitment). Given that commitment, the development of the RP can be furthered by the positive heuristic guiding chemists in how to study the nature and properties of the discrete entities and how to build the theory relating the properties of these entities to macroscopic chemical phenomena.

Within such a programme, specific theoretical ideas will be developed in response to the positive heuristic: so now we tend to distinguish atoms, molecules, ions, etc. Particular models and concepts – a planetary model of the atom, the notion of discrete atomic orbitals, etc. – may be introduced, developed and perhaps sometimes abandoned. This does not threaten the programme itself as long as these refutable variants are consistent with the hard core and no aspect of the hard core itself is put aside. For example, the notion of the atom, and the role it plays within this system, has shifted considerably over time (Taber 2003), but this has not brought into question the core ideas that matter has structure at the submicroscopic level and that the properties of the quanta of matter at this level provide a basis for explaining chemical phenomena: rather such changes are part of the process of considering how best to model and understand the submicroscopic structures that are assumed to exist (i.e. these changes occur *within* and informed *by* the programme).

Lakatos (1970) thought that the notion of RP could apply well beyond the natural sciences – for example, psychoanalysis, Marxism and astrology could all be considered to be RP – but that a *scientific* RP remains 'progressive' in the sense that new theory adds to the protective belt (without simply explaining away difficult results) and empirical work continues to respond to and stimulate theoretical developments.

57.13.2 Research in Science Education as a Scientific Enterprise

Lakatos's work can be considered to offer a form of synthesis of the thesis of Kuhn and the antithesis of Popper. Where Kuhn's descriptive analysis lacked any means to distinguish science from non-science or good science from bad, Lakatos's ideas do offer a basis for deciding when a RP is 'progressive' and so deserves support from scientists. According to Lakatos, several RP may operate in parallel, as long as each offers evidence of being progressive. However, once a programme is clearly degenerating, it should only hold a scientist's loyalty until a new promising alternative appears.

Where Popper offers a prescription that is difficult to operationalise – as all scientific theories are formally refuted on a regular basis and all refutations can be explained away with sufficient imagination – Lakatos offers an analysis that is tolerant of individual failures, so long as the general trend within a programme clearly shows development. Gilbert and Swift (1985) characterised research in the Piagetian traditions and the ACM as co-existing Lakatosian RP in science education. Lakatos's approach not only has the potential to distinguish progressive (and so scientific) programmes from degenerating programmes but also highlights how within a genuine RP there is heuristic guidance for moving the field forward. This can be potentially very valuable to researchers (and new research students), providing research traditions *are conceptualised as* RP (in Lakatos's sense), where the features that offer heuristic value are made explicit.

Given the considerations explored above which lead educational research to draw upon such a multiplicity of methodologies, it seems unlikely that the adoption of an explicit Lakatosian perspective would allow the fields of science education to be reorganised (substantially or simply conceptually) into a number of discrete programmes with each developing the kind of disciplinary matrix Kuhn recognised in the natural science: RP in science education are likely to remain too pluralistic to seem like normal science.

However, a Lakatosian analysis can identify key commitments for particular strands of work, identify clear directions for those strands and make it easier to judge whether they are empirically or theoretically progressive at any point in time. That would certainly be valuable, both in the task of helping those in the field to appreciate the sense in which they are involved in a scientific enterprise – despite the multiplicity of theoretical perspectives and methodologies that will continue to be adopted across, and sometimes within, programmes – and in guiding researchers, journal reviewers and funding agencies in making rational choices regarding where to commit valuable and limited resources.

According to Lakatos, RP are adumbrated at the outset; and it is possible to identify elements of such programmes in science education. One tradition of work in science education (exploring the contingent nature of learning in science building on the tradition of the ACM, drawing initially on a personal constructivist perspective) has been analysed in some detail as a Lakatosian RP (Taber 2006a, 2009b). This analysis identifies a number of hard-core assumptions that were set out in seminal papers that established the programme and which have provided the taken-for-granted commitments of those taking up work in this tradition. The assumptions give rise naturally to a set of initial RQ (i.e. a basis for the positive heuristic) that have been answered (and refined) to differing extents through the development of a range of auxiliary theories and constructs that act as refutable variants of the programme. Arguably (i.e. according to this analysis) this has been a progressive programme, as it has developed its theoretical apparatus in relation to an expanding base of empirical investigations and results.

Despite this, there is clearly something of a shift away from a core aspect of the programme (the strong focus on learning as personal sense making and knowledge construction). This implies that many researchers see this tradition as having less potential for progress than alternative perspectives. This may be so, as undoubtedly as the programme has proceeded the questions to be answered have become more nuanced, and the means of answering those questions have required more effort (e.g. long-term, in-depth study of individuals rather than surveying groups of learners at one point in time).

Without a shared recognition of the heuristics of established RP, decisions about what RQ to follow up will be made by individual graduate students and researchers, with limited moderation by the community. Arguably that tends to be the way of scholarship in the humanities, but it is not how science is organised (Ziman 1968). Individuals will naturally tend to make decisions in their own interest, which is why the apparatus of a scientific enterprise (peer review for publication, funding opportunities, appointment and promotion committees) needs to be well informed about the state of a field to put the right motivations in place for individuals. The mechanisms of RP offer support for that community apparatus. The analysis of the programme of research into the contingent nature of learning in science (Taber 2009b) is certainly not beyond criticism and indeed invites alternative conceptualisations. However, it does show the feasibility of adopting Lakatos's approach as one means of seeking to take seriously the challenge of making science education a scientific enterprise.

57.14 Conclusion

In conclusion, research in science education may never resemble Kuhn's normal science, because of the complexity of educational phenomena, the difficulty of maintaining the integrity of many of those phenomena outside of naturalistic settings and the nature of teachers and learners as individuals each constructing their own understandings of the world and entitled to negotiate the basis on which they might participate in our research. It is likely that many areas of work in science education will continue to draw upon diverse theoretical perspectives and to call upon an eclectic range of methodological tools selected to meet the needs of different specific studies.

However, science education can certainly be a 'sort of science', albeit an 'extraordinary' sort of science: organised to ensure that the adoption of diverse perspectives and methodologies is informed by a meta-methodology and so always based upon rational choices deriving from a sound understanding of the current state of knowledge in the field. Given the nature of educational phenomena, the convergent channelling of Kuhnian paradigms would be too limiting and restrictive. Yet giving researchers completely 'free range' to seek their own problem and develop their own original approaches to solve it – often seen as the path to academic recognition in the humanities – is unlikely to lead to optimum progress in addressing pressing educational problems. Lakatos's notion of RP offers a middle road here, as RP provide guidance to researchers about research priorities and allow the community to take stock of progress, without the blinkers of 'the' paradigm. The way in which educational researchers are commonly trained to develop their projects, with a strong open-ended phase to creatively consider divergent options before making rational and justifiable methodological choices, can be framed (i.e. guided, but not prematurely constrained) within the heuristic guidance of a progressive RP. This would allow the principled development of research designs on a problem-by-problem basis, but guided by the heuristics of an established tradition that the research community considers to be progressive. Arguably, that offers a 'sort of science' that best suits the field of science education.

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Chapter 58
History, Philosophy, and Sociology of Science and Science-Technology-Society Traditions in Science Education: Continuities and Discontinuities

Veli-Matti Vesterinen, María-Antonia Manassero-Mas, and Ángel Vázquez-Alonso

58.1 Introduction

Since the Sputnik crisis in the late 1950s, Western science education has been continuously concerned with the provision of quality training for task-force scientists. Successive innovations did not seem to change the essential aim of traditional school science education, that is, to prepare a small minority of students to become scientists. This approach was plagued with three major omnipresent failures: students' disaffection towards scientific subjects; mythical and distorted image of science conveyed to students, and failure of school science to make students learn science in a meaningful manner, to include the transmission of a view of science which did not account for the broader, sociopolitical sphere of production and application of scientific knowledge (Aikenhead 2006). A humanistic perspective in school science education was thus developed to articulate the range of social, cultural, historical, and political dimensions of science education and to challenge traditional ideas of science as a value-free enterprise (Aikenhead 2006; Donnelly 2004).

The purpose of this chapter is to account for the innovative processes that pioneered the introduction of content related to the history, philosophy, and sociology of science and technology into science education curricula. Our aim is twofold: first, to follow the development of the movements and labels which accompanied these innovative processes, in particular, the science-technology-society

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(STS) movement, which was born in the 1970s, the ongoing debates surrounding the concept of scientific literacy, introduced in 1950, and the more recent stream of studies on the nature of science and socioscientific issues; second, to show that, beyond labels and names, there are some underlying similarities across all such movements. Similarities are especially important when the continuity of the innovative process with its corresponding movements and ideas is highlighted over the potential differences. A revisit of the history, aims, debates, implementation, and research of the science-technology-society movement is an opportunity to better understand and connect the current proposals for science education (Millar and Osborne 1998).

The scope of the approach adopted to develop such purposes has some specific limitations and rationales. The reflections presented here are restricted to precollege science education where the innovations under scrutiny may have a large impact on citizens' scientific literacy, the public understanding of science, and yet their pedagogical implementation is still scarce in traditional school science curricula. In order to comply with the space limitations, some decisions have also been made regarding the spread of cases covered in our account of continuities and discontinuities under scrutiny. The method selected consists of a qualitative comparison and evaluation of the starting point of the follow-up (STS) and the current situation of humanistic practices in science education. A choice has been made for the latter in favor of the former-mentioned trio of movements (scientific literacy, nature of science, and socioscientific issues). The selection of paradigms draws on the appreciation of both their relevance in the current science education research and their strong relationship to the history, philosophy, and sociology of science tradition, which is the underlying criterion of the search for the (dis)continuities.

Summing up, the account starts from the analysis of the STS movement, as the first relevant implementation of the history, philosophy, and sociology of science tradition in science education, and then it progresses to the selected movements, as the current relevant areas where one can find the history, philosophy, and sociology of science tradition under new forms and contexts. Finally, a conclusion of the account highlights some current debates and outstanding issues in the field.

58.2 Science-Technology-Society (STS) Movement

The science-technology-society (STS) movement emerged from the social upheavals of the 1960s and early 1970s. In the social arena, the Cold War era around the 1950s had enlightened the consciousness of humankind of the likelihood of a global nuclear holocaust, while the environmental movement of 1960s brought to the forefront the increasing damage that industrialization had caused to the environment (e.g., acid rain). During the 1960s several academics and activists such as Lewis Mumford (1967–1970) and Jacques Ellul (1964) as well as consumer activist Ralph Nader (1965) began to express doubts about the presumed benevolence of the new technologies. Because science and engineering sat at the core of those issues, the global concern over these challenges definitively pointed to the responsibilities of scientists and engineers in solving them. In response to this state of affairs, science-technology-society courses were first established in engineering colleges to educate science and engineering students about the societal impact of their work (Cutcliffe 1990). The STS movement in higher education was both an academic field and a social movement, as the scholarly pursuit of science and technology studies was intertwined with the more activist stance of teachers and political organizers (see Cozzens 1993).

Eventually the movement had some effect also on school science education, as it was expected that a better school science education would allow not only scientists and engineers but also general citizens to cope effectively with these challenges. By the 1970s, some researchers became focused on developing materials addressing the complex relationships between science, technology, and society with the purpose of improving school science education. They worked on the idea that science would become more meaningful to students when its relationships with technology were made apparent and how technology, in turn, directed society and the reverse from society to science. A school science education movement called science-technology-society (STS) was born out of these initial efforts for teaching science in the broader context of the mutual relationships between science, technology, and society.

The STS approach involved also a shift from the positivist, non-contextual philosophical stance of traditional science education towards a contextualized, post-positivist view of science (and thus acknowledging the influences of technology, society, culture, ethics, politics, etc.). In the 1960s, the traditional, positivist image of science had been challenged in the academic arena by the historical, philosophical, and sociological analysis of scientists' work, thus providing a new and different image of science. At the time, science education was strictly based on the positivist view of science, whereby knowledge of the natural sciences was kept separate from current history, philosophy, and sociology of science. The emerging epistemological reflection supported by science and technology studies was thus a real challenge to traditional views on curricula and science textbooks. Emerging from the environmental, civil rights, and consumerism movements and preceded by new views of science presented in Thomas Kuhn's (1962) *The Structure of Scientific Revolutions* and post-WWII attention to history, philosophy, and sociology of science in science instruction,[1] Jim Gallagher (1971) proposed that understanding the interrelationships of science, technology, and society should be one of the main goals of school science education. The rationale for STS science education was clearly formulated in his description of a new goal for science education:

> For future citizens in a democratic society, understanding the relationships of science, technology and society may be as important as understanding the concepts and processes of science. (Ibid., p. 337)

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[1] See, e.g., Conant (1957), Holton et al. (1970), Klopfer (1963), and Klopfer and Watson (1957).

Although the STS movement in higher education began as an academic endeavor for understanding the social issues linked to developments in science and technology, over the course of the decades, it has blended together with sociological and philosophical research about the development of science and technology to constitute an interdisciplinary field of science and technology studies (Sismondo 2010). Building on the constantly developing field of science and technology studies, as well as on research on science, environmental, and citizenship education, STS has remained a major theme in many school science curriculum reforms both in North America and in Europe at least since the publication of Paul Hurd's (1975) article *Science, Technology, and Society: New Goals for Interdisciplinary Science Teaching*. In fact, during the past 40 years, STS has evolved into an umbrella term that includes a wide variety of different views about the connections between science, technology, and environment and approaches to teaching science.[2] According to Glen Aikenhead (1994, 2006), the core conceptual framework for STS in school science education now incorporates two domains of science studies: *internal sociology of science*, interested in the social interactions between scientists and their communal, epistemic, and ontological values, and *external sociology of science*, interested in the interactions of science and scientists with the larger cultural milieu (see Ziman 1984). The emphasis placed on either of these two domains and whether the issues are discussed implicitly or explicitly have varied from project to project and program to program (Aikenhead 1994).

The multifaceted and complex nature of the STS movement has meant that the movement struggled to achieve any kind of internal consolidation. Rather it became the starter for the worldwide development of many slogans (such as socioscientific issues and nature of science), which can be deemed a sign of the developmental power of the STS approach. We argue that these slogans fit the very tenets of STS education, whose complex ecology has been labeled by Aikenhead (2003) in his fortunate title "A Rose by Any Other Name."

58.2.1 Environmental Education and Education for Sustainable Development

From the beginning, the STS movement has had its roots in the planetary fear for nuclear holocaust and in the growing alarm about the environmental impact of science and technology-based artifacts (e.g., weapons and polluting chemicals). The emergence of the environmental crisis in the 1960s documented by works such as Rachel Carson's (1962) *Silent Spring* and Paul Ehrlich's (1968) *The Population Bomb* caused increasing concern from the side of the public about the responsibilities of scientists and citizens, who manage these affairs. This concern had a profound effect also on educational trends. In 1977, the Intergovernmental Conference on Environment Education set the objectives for students' awareness,

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[2] For more detailed history of the evolution of STS programs, see Aikenhead (2003).

knowledge, attitude, skills, and participation and defined the following goals for environmental education:

> 1. To foster clear awareness of, and concern about, economic, social, political and ecological inter-dependence in urban and rural areas.
> 2. To provide every person with opportunities to acquire the knowledge, values, attitudes, commitment and skills needed to protect and improve the environment.
> 3. To create new patterns of behavior of individuals, groups and society as a whole, towards the environment. (UNESCO 1977, p. 26)

When the term of "sustainable development" was first introduced in the Brundtland Report by the World Commission on Environment and Development (United Nations 1987), it linked the environmental problems to issues of global equity and justice, such as income and resource distribution, poverty alleviation, and gender equality. Gradually, global environmental problems such as climate change and biodiversity reduction also replaced local problems as the main areas of concern and public debate. This reframing of environmentalism had its effects on educational trends; instead of simply referring to environmental education, UNESCO and other international organizations began to promote education for sustainable development (see, e.g., Jones et al. 2010; UNESCO 2005).

The vocabulary of sustainable development also had an effect on scientific practice. Although the political and societal processes preponderantly shaped the sustainable development movement during the late 1980s and early 1990s, by the beginning of the twenty-first century, a new field of sustainability science was emerging (see, e.g., Kates et al. 2001). Promoted by international scientific programs, scientific academies, and independent networks of scientists, sustainability science seeks to understand the fundamental character of interactions between nature, science, technology, and society as well as to "facilitate the move toward a more just and sustainable world as part of the politics of the practical" (Carter 2008, p. 176). Sustainability science is a transdisciplinary approach defined more by the problems it addresses than by the disciplines it employs and it seeks to advance both knowledge and action towards a more sustainable world (Clark 2007). It acknowledges the contextualized, post-positivist view of science promoted by the post-Kuhnian science and technology studies, recognizes that techno-scientific practice cannot stand outside the nature-society system, and seeks to promote social change (Colucci-Gray et al. 2006; Colucci-Gray et al. 2012). Thus, it seeks to involve not only scientists but also "practitioners, and citizens in setting priorities, creating new knowledge, evaluating its possible consequences, and testing it in action" (Friibergh Workshop on Sustainability Science 2000).

With its roots deeply set in the environmental literature, the STS movement shared many common characteristics with environmental education and education for sustainable development. Some science educators even advocated integrating environmental education into more socioscientific issue-driven science-technology-society-environment (STSE) education with the goal of fostering a voice of active citizenship in students (e.g., Hodson 1994, 2003; Pedretti 1997, 2003). Also education for sustainable development shares the goal of preparing the students for civic engagement. This means not only providing the students with knowledge about socioscientific issues and models for informed choices in their everyday life but also building capacity to think critically about what the experts say and participate in the process of developing and testing suitable ideas (see Vare and Scott 2007). As sustainability science is still a relatively new field of study, it is only just beginning to have impact on the research and practice of science education (see, e.g., Carter 2008; Colucci-Gray et al. 2006, 2012).

58.2.2 Socioscientific Issues (SSI) Approach

In the past four decades, STS education has become a relatively complex and diffuse field, which displays a wide variety of approaches and some huge variations in the proportion of STS instruction devoted to societal issues: STS education can range from small text boxes infused into science textbooks to highly specialized courses addressing STS issues (see, e.g., Aikenhead 1994; Pedretti and Nazir 2011). The dissatisfaction with the lack of focused and functional models for STS instruction however was the promoter for new ways forward. One of them is the science instructional proposal called socioscientific issues (SSI).

Promoters of the SSI approach claim that STS education has been missing a coherent developmental or sociological framework and thus “has been relegated to brief mentions in current school science textbooks as well as in science teacher preparation texts” (Zeidler et al. 2005, p. 359). The SSI instruction stresses the factors associated with formal reasoning (argumentation) and the moral principles underlying science-based issues, and it focuses on controversial social issues with conceptual and/or procedural links to science and technology. The socioscientific cases used in SSI instruction are usually open-ended problems, the solutions to which can be informed by scientific principles, theories, and data, though they are not fully determined by scientific or technological considerations (Sadler 2011). Through cases students become involved in social argumentation and reflection aimed at developing cognitive, critical thinking skills and affective moral development.[3]

The STS and SSI movement share the goal of better preparing learners to engage in discussions and decisions related to socially relevant issues associated with science or technology. The SSI movement seems to share similar visions, tenets, and pedagogies with STS, although it may present and argue them differently, so that its promoters claim SSI are “beyond STS” (Zeidler et al. 2005). Much like the

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[3] Proponents of SSI instruction have suggested various instructional models for utilizing these socioscientific case studies to better achieve these aims (see, e.g., Sadler 2011). For example, Pedretti (2003) suggested a pedagogical model developed from Ratcliffe (1997) and which includes the following stages:

1. Option: Identify alternative courses of action for an issue.
2. Criteria: Develop suitable criteria for comparing alternative actions.
3. Information: Clarify general and scientific knowledge/evidence for criteria.
4. Survey: Evaluate pros/cons of each alternative against criteria selected.
5. Choice: Make a decision based on the analysis undertaken.
6. Review: Evaluate decision-making process identifying feasible improvements.

STSE education, SSI emphasizes informed citizenry and even positions promoting citizenship as the primary goal of science education (Sadler 2011). The advocates of SSI have argued that STS and STSE approaches with similar goals do not give sufficient attention to ethical issues to help the development of the moral and emotional development of students (e.g., Zeidler et al. 2005). SSI is seen as a "broader term that subsumes all that STS has to offer, while also considering the ethical dimensions of science, the moral reasoning of the child, and the emotional development of the student" (Zeidler et al. 2002, p. 344). The advocates of SSI instruction maintain that the STS approach does not appropriately deal with scientific and technological controversies and ethical environmental dilemmas, because it does not exploit the inherent pedagogical power of discourse in socioscientific issues, such as reasoned argumentation, explicit nature of science considerations, as well as emotive, developmental, cultural, or epistemological connections within the issues themselves.

Though promoters of SSI claim that their stress on social, developmental, argumentative, and moral issues is important enough to deserve an epistemological demarcation from the STS approach, the points of similarity between the two approaches seem to surpass the points of distinctiveness. Despite their criticism towards STS, even the advocates of SSI widely acknowledge the parenthood of STS in relation to SSI (e.g., Tal and Kedmi 2006; Zeidler et al. 2005). Besides, because understanding scientific argumentation and justification are fundamental skills in decision making about socioscientific issues, SSI movement is also closely related to the notion of nature of science, discussed in more detail in Sect. 58.4.

58.2.3 Systematizations and Evaluations of STS and SSI

The works of systematization provided by Aikenhead (1994) and Pedretti and Nazir (2011) help to understand the complexity of the STS field. Aikenhead suggested an interesting taxonomy of STS education that classifies the wide variety of STS projects into a spectrum of eight categories, from traditional science to STS science. This taxonomy expresses the relative proportion of the innovative STS elements compared to traditional science content, the way these elements are presented, and the relative weight of STS content in the educational assessment.

1. *Motivation by STS content:* Just a mention of STS content in order to make a lesson more interesting and students are not assessed on the STS content.
2. *Casual infusion of STS content:* A short non-cohesive STS content is attached onto the traditional science topic. Students are superficially assessed on the STS content.
3. *Purposeful infusion of STS content:* A series of short cohesive STS content is systematically integrated into science topics. Part of the students' assessment includes STS content.
4. *Singular discipline through STS content:* STS content organizes and sequences traditional science content. Understanding STS content is assessed, though still less than science content.

5. *Science through STS content:* STS content dictates, organizes, and sequences multidisciplinary science content. Students' understanding of STS content is assessed, though still less than science content.
6. *Science along with STS content:* STS content is the focus; relevant science content enriches learning. Students are assessed equally on the STS and science content.
7. *Infusion of science into STS content:* STS content is the focus and broad scientific principles are mentioned. Students are primarily assessed on STS content and only partially on science content.
8. *STS content:* A major technology or social issue is studied and science content is only mentioned to make links to science. Students are not assessed on pure science content.

Further, Pedretti and Nazir's (2011) review of 40 years of research on STS education identified six currents in STS education: application/design, historical, logical reasoning, value-centered, sociocultural, and socioeconomic currents that explicitly reflect the philosophical, historical, and sociological basis of STS. The first three currents appear to place more emphasis on science-oriented issues, while the other three emphasize socially oriented issues:

1. *The application/design current* focuses on the link between science and technology and solving utilitarian problems through designing new technology or modifying existing technology (technical and inquiry skills). It combines cognitive skills with pragmatic, experiential, creative work in applying scientific knowledge.
2. *The historical current* highlights science as a human endeavor through understanding of the historical and sociocultural embeddedness of scientific ideas and scientists' work. It promotes the intrinsic values of science (exciting, interesting, and necessary pursuit) through affective, creative, and reflexive approaches, where STS and nature of science overlap.
3. *The logical reasoning current* addresses controversial socioscientific issues through the interactions between science, technology, society, and environment. It develops competences on understanding multiple perspectives, critical thinking, and decision making.
4. *The value-centered current* develops moral and ethical values tied to controversial socioscientific issues. Again, it develops understanding multiple perspectives, critical thinking, and decision making on affective and moral issues.
5. *The sociocultural current* addresses science and technology as social institutions to understand its internal organization and external links to politics, economics, and culture.
6. *The socio-ecojustice current* addresses the sociopolitical aspects of science and science education to educate civic responsibility that allows citizens to act on the social and ecological, local, and global problems of the world in search for justice.

By describing value-centered and ecojustice currents, it seems clear that in their review of the STS movement, also Pedretti and Nazir (2011) hold the underlying implicit assumption of a direct parenthood between STS and SSI movements.

After years of researching and teaching through STS materials, Bennett et al. (2007) undertook a systematic evaluation of the effects of context-based and STS approaches in the teaching of secondary science. The study reviews17 experimental studies from eight different countries and the overall findings indicate improvements in attitudes and motivation towards science, while the understanding of scientific concepts and ideas is comparable to that of conventional approaches. Specifically, the review suggests that there is reasonable evidence of the following:

- Students of both genders in classes using a context-based/STS approach held significantly more positive attitudes to science than peers in classes using a traditional approach.
- A context-based/STS approach to teaching science narrowed the gap between boys and girls in their attitudes to science.
- In cases where boys enjoyed the materials significantly more than girls, this was due to the nature of the practical work in the unit. In cases where girls enjoyed context-based materials significantly more than boys, this was because of the nonpractical activities in the unit.

The review also suggests there is some evidence of the following:

- Students in classes using a context-based approach perceived significantly more often a close link between science, technology, and society and showed significantly better conceptual understanding of science than their peers in traditional classes.
- Girls in classes using a context-based/STS approach developed a significantly more positive attitude towards taking a science career compared with boys in these classes.
- Girls in classes using a context-based/STS approach showed equal conceptual understanding of science as male peers in the same classes.
- Lower-ability pupils in classes using a context-based/STS approach held significantly more positive attitudes to science and better conceptual understanding of science than lower-ability pupils in classes using a traditional approach and better attitudes than high-ability peers in the same classes.

Despite the limitations and caveats of the reviewed studies, Bennett and colleagues (2007) acknowledge that the evidence is reliable and valid in supporting the use of contexts as a starting point in science teaching: there are considerable benefits in terms of attitudes to school science and no disadvantages in the development of understanding science.

Sadler (2004) reviewed the literature on SSI to assess its relationship with significant variables of learning scientific literacy, such as skills of informal reasoning and argumentation, conceptualizations of nature of science, evaluation of information, and the development of conceptual understanding of science content. The review by Sadler (2004) does not claim that students will become better informal thinkers, capable of analyzing complex arguments and of developing mature epistemologies of science, by simply being exposed to SSI. On the contrary, the review and further studies (see, e.g., Sadler 2011) consistently suggest that improvements in students' reasoning and argumentation are quite difficult to achieve, and in fact the findings show that reasoning that takes into account scientific evidence is a highly elusive aim as students easily ignore evidence when it is not in accordance with their own claims or previous attitudes. However, SSI studies provide examples of the relative stability of students' ways of argumentation and decision making, though these processes are so deeply rooted in their identity and culture that resist taking into account other elements that go against their own personal points of view. Further, SSI studies can provide an important stimulus for working on the informal reasoning and argumentation skills, the nature of science conceptualizations, the skills of evaluation of information, and the development of conceptual understanding of science content.

58.3 Scientific and Technological Literacy

Since it was first introduced over 50 years ago and especially in the last three decades, scientific literacy has become a central educational objective of science education worldwide (Hurd 1998; Oliver et al. 2001; Dillon 2009). In fact, scientific literacy has developed into an umbrella term covering most aims of science education (DeBoer 2000; Laugksch 2000). In recent years also technological literacy has gained grounds as a similar central tenet for modern technology education (Wonacott 2001). We argue that the STS movement and its derivatives have informed discussion on both scientific literacy and technological literacy. In the following subsections, we summarize the development of these two concepts and their underlining similarities as well as their connections with history, philosophy, and sociology of science, as well as with the STS movement and its derivatives.

58.3.1 Scientific Literacy

The launch of the Sputnik I in 1957 and the following science policy crisis in the United States had a profound effect on science education. The United States as well as countless other nations saw a spur of initiatives aimed at fostering new generations of engineers and scientists, and the number of science-oriented programs mushroomed. The main focus of such programs and initiatives was on training the most gifted students to become scientists and engineers. Although a concern for the public understanding of science dates back at least to the early years of the nineteenth century and had influential proponents such as the educational reformist John Dewey, the concept of scientific literacy as a goal for science education surfaced in the period of reindustrialization after the Second World War. The concept was introduced by Paul Hurd (1958) and Richard McCurdy (1958) at the height of the Sputnik crisis. The interest in the notion of scientific literacy following the Sputnik crisis was focused on improving public understanding and support for the scientific enterprise and industrial programs (see Fitzpatrick 1960; Waterman 1960).

In the 1960s and 1970s, the concept of scientific literacy was being debated, defined, and reconceptualized countless of times.[4] Much like the STS movement, formulations of scientific literacy in the 1960s and 1970s were inspired by new academic research on science and technology studies, which viewed science and technology as socially embedded enterprises, as well as environmental and civil rights movements. Many science educators were also disappointed about the outcomes of a school science education targeted towards a minority of students interested in continuing towards university science and engineering courses rather than developing the capabilities of all students to function as responsible citizens in a world increasingly affected by science and technology. Thus, the definitions of scientific literacy shared many educational goals with the STS movement. For example, Pella and colleagues (1966) suggested that scientific literacy comprises understanding of the basic notions of science as well as understanding the ethics embedded in the scientists' work, the interrelationships of science and society, and the differences between science and technology.

In the late 1970s and 1980s, the advocates of STS education began to dominate the discussion on scientific literacy (DeBoer 2000). The National Science Teachers' Association (NSTA) position statement from 1982 entitled *Science-Technology-Society: Science Education for the 1980s* stated that the goal of school science education was "to develop scientifically literate individuals who understand how science, technology, and society influence one another and who are able to use this knowledge in their everyday decision-making" (NSTA 1982, quoted in Yager 1996, p. 4). Several other countries had similar STS-based programs striving for scientific literacy, such as *Science in Society* (Lewis 1981) and *Science in a Social Context (SISCON)* (Solomon 1983) in the United Kingdom, *Project Leerpakket Ontwikkeling Natuurkunde (PLON)* (see Eijkelhof and Lijnse 1988) in the Netherlands, and *SciencePlus* (Atlantic Science Curriculum Project 1986, 1987, 1988) in Canada. One of the reasons for the growth of emphasis on STS approaches was the recognized failure of science education reforms with a theoretical disciplinary emphasis which were implemented since after the Sputnik crisis (Matthews 1994). The urgency of the need for a change of focus for science education was supported by the publication in 1983 of *A Nation at Risk* (National Commission on Excellence in Education 1983), which documented how, in spite of the efforts following the Sputnik crisis, a vast majority of students were still not interested in science and they learned very little science. This "science literacy crisis" urged for the adoption of more contextual approaches to science education and the goal of scientific literacy for all.

The disenchantment with the results of traditional programs was not the only driving force behind the change. Influenced by civil rights and environmental movements as well as the tradition of liberal education, researchers such as Chen and Novik (1984) and Thomas and Durant (1987) saw scientific literacy as a means to promote more democratic and equal decision making. Scholars still justify the need for a scientifically literate society upon rationales that evoke many of the aims

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[4] See, for instance, Agin (1974), Daugs (1970), Gabel (1976), Klopfer (1969), O'Hearn (1976), Pella (1967), Pella et al. (1966), and Shen (1975).

of the STS approach, such as socioeconomic development, cultural development, personal autonomy, usefulness for everyday life, decision making, democratic participation in public issues related to science and technology, and ethical responsibility of scientists, technicians, politicians, and citizens (see, e.g., Laugksch 2000). Such reconceptualizations of scientific literacy towards scientific citizenship have laid the ground for new approaches such as STSE and SSI. The influence has been reciprocal, as proponents of STS and its derivatives have been very active in debates on the meaning and purpose of scientific literacy. For example, Zeidler and colleagues (2005) reconceptualize SSI elements of "functional scientific literacy," identifying four areas of pedagogical importance in supporting students' cognitive and moral development: (i) nature of science issues, (ii) classroom discourse issues, (iii) cultural issues, and (iv) care-based issues.

Many advocates of the STS movement and its derivatives go beyond traditional definitions of literacy as knowledge and skills and advocate social action as the highest goal of science education (DeBoer 2000). Much like in science studies, where in the new interdisciplinary fields such as the women's studies researchers began to see themselves as activists working for a change towards more equal and societally conscious science, also in science education some researchers began to advocate a similar activism oriented towards a more equitable and democratic society. These new perspectives on the meaning and purpose of science education have been influenced by a broad array of work from science studies, feminist studies, sociocultural theory, and critical pedagogy. Based on such reflections STS tradition has actively reconceptualized science education as an instrument of social and political engagement and sociopolitical action, which is evident, for example, in the works of Wolff-Michael Roth and Jacques Désautels (2002) and Wildson dos Santos (2008).

58.3.2 Scientific Literacy as Literacy for All

Much like what we saw with the STS movement, differences that appear between the various definitions of scientific literacy proposed by various specialists and the level of substantive disagreement about its content seem to highlight the complexity of concept (Bybee 1997; Gil and Vilches 2001; Manassero and Vázquez 2001). For example, various stakeholders interpret the word "literacy" in numerous different ways. In science education research, scientific literacy is defined from a variety of perspectives: as a motto, which covers a broad international movement (Aikenhead 2003); as a metaphor that expresses the aims and objectives of science education (Bybee 1997); and as a cultural myth that indicates the ideal to pursue (Shamos 1995).

To analyze the wide variety of meanings of scientific literacy, Roberts (2007) suggests a heuristic tool featuring two extreme positions, which he calls Vision I and Vision II. Vision I corresponds to the literacy within science, that is, the decontextualized products (facts, laws, theories, etc.) and processes of science. According to Vision I school science should give pupils knowledge and skills to approach situations as a professional scientist would. Vision II refers to literacy that a student would be likely to require as a citizen acting in situations outside the scientific world, or not entirely belonging to science, although clearly related to it. In Vision II the aim of the education is enabling students to approach situations as citizens who are well informed about science. Proponents of the STS movement and its derivatives have usually been positioned more towards Vision II of science education (see, e.g., Zeidler et al. 2005). Having these two poles of the heuristic tool in mind helps to analyze the relative proportion of these possibly conflicting goals in various definitions and descriptions of scientific literacy (much in a similar manner as the Aikenhead's STS categories help to analyze the amount of STS content in a project).

Paralleling the aims of general literacy (reading and writing), scientific literacy has since the science literacy crisis of the 1980s been increasingly associated with its complement of being a literacy "for all," especially in the school years before choosing a major. The concept of scientific literacy has thus been increasingly associated with its complement "science for all," assuming they are inseparable, but without clearly specifying what they mean, thus creating some confusion and debate. Tippins et al. (1999) argue that scientific literacy and science for all are potentially two contradictory concepts; on the one hand, the idea of science for all requires that no one is excluded from science education, thus creating a need for inclusive and meaningful school science, which has relevance to all students (see Vázquez et al. 2005; Vázquez and Manassero 2007); on the other hand, scientific literacy appears to be based on a certain set of knowledge, skills, and attitudes that students must seek, for example, the contents of the *Benchmarks* (American Association for the Advancement of Science 1993) or the *NSE Standards* (National Research Council 1996). It seems that the goal of science for all requires different contents of school science for diverse learners, while scientific literacy implies the idea that all science programs must meet the same set of criteria. Students can be taught notions of science apparently needed to acquire knowledge and skills required for scientific literacy, but it may be that learning such knowledge and skills will prove to be uninteresting and of little value to the students (Manassero and Vázquez 2001). Thus, there seems to be an obvious tension between scientific literacy and science for all. This tension is at the core of the debates about the goals of science education and, in general, of all basic education that must be common and inclusive (Acevedo et al. 2003; Tippins et al. 1999) and of the demands of higher education and the benchmarking needs for preparation for a career as a scientist (Abd-El-Khalick 2012).

From recent international research in science education and current educational reform initiatives, the progressive visions of scientific literacy encompass broad conceptual frameworks that entail basic knowledge of science (scientific facts, laws, and theories) and increased emphasis on the knowledge about science, that is, understanding about the processes and methods used to develop such knowledge (scientific inquiry) as well as the history, sociology, and epistemology of scientific knowledge (nature of science). In particular, students are expected to develop some specific scientific knowledge, skills, and attitudes, which involve understanding science as a "way of knowing" (absolutely necessary, if informed decisions are to be made), decision making on scientifically based personal and societal issues that increasingly confront the students, as well as the development of a commitment to the moral and ethical dimensions of science education that include the students' social and character development. Such decisions represent a functional degree of scientific literacy as they necessarily involve careful evaluation of scientific claims by discerning connections among evidence, inferences, and conclusions through the ability to analyze, synthesize, and evaluate information. A degree of scientific literacy also entails practice and experience in developing scientific attitudes such as skepticism, open-mindedness, critical thinking, recognizing multiple forms of inquiry, accepting ambiguity, searching for data-driven knowledge, dealing sensibly with moral reasoning and ethical issues, and understanding the connections that are inherent among socioscientific issues (Zeidler 2001).

Since scientific literacy is closely linked to social, cultural, and ideological aims of education, it is virtually impossible to establish a complete model of school science curricula to better achieve it. Although the aims, purposes, and objectives might be widely shared, it might be unrealistic to expect all students to achieve the same specific objectives. As different societies and social groups interact differently with science and technology, the standard-based curricula should consider only general references that should be developed in the classroom through specific contexts. In practice, scientific literacy can be grasped in different ways and with different levels of complexity to adapt to different contexts and students. However, this contextualization should keep the general framework and the principle of equity. We maintain that the paradigm of science-technology-society (STS) is best able to guide the selection of basic content that is relevant and useful for all students and also by providing us with methodological guidelines that contextualize into practice this important educational innovation (see Acevedo et al. 2003).

58.3.3 Technological Literacy

Traditional technology education was based on the industrial model of technology, which during the past decades and in the new era of information technology became apparently outdated. In a technologically mediated world, technological literacy requires understanding about the impact of new and emerging technologies on society and the environment (Dakers 2006). The notion of technological literacy has been established as the central tenet for modern technology education (Wonacott 2001).

Much like scientific literacy calls for a science education for all and focuses on the nature of science, processes of scientific research, and interaction of science and society, technological literacy calls for a technology education for all and focuses on the nature of technology, process of technological design, and interaction of technology and society (see, e.g., ITEA 2000). Again, much like with scientific literacy, the goal of technology education is increasingly seen in promoting more democratic and equal decision-making processes and social action. One of the most comprehensive classifications of the goals of technology education was the model based on functional competencies described by Layton (1993). The functional competencies included:

1. *Technological awareness (receiver competence):* The ability to recognize and acknowledge the possibilities of technology in use
2. *Technological application (user competence):* The ability to use technology
3. *Technological capability (maker competence):* The ability to design and make artifacts
4. *Technological impact assessment (monitoring competence):* The ability to assess the personal and social implications of use of technologies
5. *Technological consciousness (paradigmatic competence):* The ability to work within a "mental set," defining what constitutes a problem, circumscribes what counts as a solution, and prescribes the criteria which technological activity is to be evaluated
6. *Technological evaluation (critic competence):* The ability to judge the worth of technological development and to step outside the "mental set" to evaluate it

In the last 20 years, the focus of technology education has moved from providing vocational skills in technology to developing critical competencies in multiple techno-literacies, which include critical computer literacy and critical multimedia literacy (Kahn and Kellner 2006). Change of focus in aims of technology education resembles the change from Vision I science education to Vision II science education (see Roberts 2007). With such new goal for technological literacy, learning and teaching technology becomes a dialogue; the teacher and students form a community with no right or wrong answers, only more or less informed interpretations (Dakers 2006).

Much like with the definitions of scientific literacy, academic science-technology-society programs have influenced definitions of technological literacy. In the 1980s, researchers in science and technology studies turned their attention to technology. MacKenzie and Wajcman's (1985) *Social Shaping of Technology* and Bijker et al. (1987) *The Social Construction of Technological Systems* paved the way for sociological accounts of technological change, much like the turn to naturalistic accounts of scientific progress revolutionized the view of scientific practice more than a decade before. Emerging sociology of technology shared theoretical and methodological lines with sociology of science and supported the unity among science and technology studies.

There are also some common misconceptions concerning technology, for instance, that science is exogenous to technology. The view that scientific discovery leads to technological innovation is so strong that it is often forgotten that there is a notable reverse flow from technology to science. Technological innovations are not just products of science – they have enormous influence also on the process of science (Stokes 1997). In fact, technology plays a huge role in the process of creating scientific knowledge as scientists create all instruments, experimental settings, and even objects of research. Direct observations of scientific phenomena usually happen at a level unattainable to our perception and phenomena are accessed through the window of technology, with instruments especially designed to refine our current scientific models (Hacking 1983). The way scientific research is done has always been and still is transformed by technological development of instrumentation (Ziman 1984). Science and technology education should take cognizance of the essential interdependence of science and technology (see, e.g., Tala 2009). We argue that instead of speaking simply about "scientific literacy" and "technological literacy," we should rather use the notion "scientific and technological literacy," which better acknowledges this bidirectional relation between science and technology (see, e.g., Fourez 1997; Holbrook 1998).

58.4 Nature of Science (NOS)

In developing scientific and technological literacy, the meta-knowledge that arises from the interdisciplinary reflections on science and technology plays an integral part. One of the central elements of STS and scientific literacy is to understand what science is, how it works, and how scientists operate. As science studies have discussed these issues and should inform teaching practice, there is a vast and complex literature on history, philosophy, and sociology of science in science education (for an overview, see, e.g., Hodson 2008, 2009). Within science education, suitable educational answers to these questions have been described by various characterizations of nature of science (NOS). In the research literature NOS is gaining ground as the most common representation of the essentials of informed and updated picture of science. NOS issues involve the most relevant features of history, philosophy, and sociology of science: what science is, how it produces valid knowledge, how it relates to technology and society, who are the scientists, how they work and relate among each other, and so on (e.g., McComas et al. 1998). The aim of producing an authentic image of science was also an important pursuit of STS approach, and as a crucial element of scientific literacy, NOS is now widely recognized to be a key concept in the curricular aims of science education all over the world.[5]

School science curricula are often filled with simplistic visions that produce mythical and deformed views of science, as, for instance, the absolutism of scientific knowledge and the stereotypical step-by-step approach of the scientific method, which hinder learning appropriate views of science and appropriate teaching of NOS in the classroom. The very question of NOS and science education arises from the inadequate images of science that school curricula and textbooks convey to students (see, e.g., Vesterinen et al. 2009; 2011). This concern was early assumed by STS movement as crucial, though modest educational aim, and today it is incorporated within definitions of scientific literacy as "learning about science" (see, e.g.,

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[5] See, for instance, Adúriz-Bravo and Izquierdo-Aymerich (2009), Hodson (2003), Matthews (2004), and McComas and Olson (1998).

Abd-El-Khalick 2012; Hodson 2009). This new aim goes beyond learning science: students should learn some basic epistemological, historical, and sociological traits of science and scientists in order to better understand how science works in the current world.

Understanding how science works is an important key for appraising scientific claims, evaluating scientific arguments, and forming a personal opinion on socioscientific issues. NOS knowledge needed for addressing socioscientific issues includes things such as the ability to distinguish between science-in-the-making, where uncertainty is to be expected, and ready-made science, on which we can rely, and the ability to recognize how sociocultural, political, economic, and religious factors can impact science, as well as the reverse (Kolstø 2001). Zeidler and colleagues (2005) even describe NOS as one of the four areas of pedagogical importance to the teaching of socioscientific issues within a curriculum striving towards scientific literacy.

58.4.1 Systematizations and Evaluations of NOS

NOS is a very complex concept, partly because it evolves and changes as our understanding of science and science itself evolves and changes. NOS brings together a variety of aspects coming from different disciplines, such as history, philosophy, sociology, and psychology of science (Vázquez et al. 2001). Thus, NOS is meta-knowledge arising from the interdisciplinary reflections on science, which have been conducted by specialists from a multitude of disciplines (Vázquez et al. 2004). In fact, NOS might present so many faces that Rudolph (2000) even contends that a single NOS does not exist at all.

Although there might not be a general agreement on the exact definition of NOS, there seems to be some sort of consensus regarding the central features of NOS that should be covered in science education (see, e.g., Lederman 2007; Niaz 2008). On the whole, the educational consensus on NOS refers to basic and relevant NOS features while keeping them highly uncontroversial: what is science; the methods science uses to construct, develop, validate, and disseminate the knowledge it produces; the features, activities, and values of the scientific community; and the internal and external links of science, such as the links between science, technology, and society. The most striking aspect of the consensual NOS features, which in turn provides further evidence in support to the teaching of NOS in schools, is the strong similarity among the different lists that researchers have proposed.[6]

In spite of consensus, there remains some divergence about the relative weight the consensual aspects should have on school science. Looking at the current mainstream NOS literature, NOS is mainly depicted as epistemology or philosophy of science, while the relationships with technology and society are much less taken

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[6] See, for instance, Abd-El-Khalick (2012), Lederman (2007), McComas and Olson (1998), and Osborne et al. (2003).

into consideration. However, an in-depth reading of the mainstream current research on NOS also evidences that broader STS social relationships, especially those referred to the works and status of the scientific community, are also recognized as part of the NOS field.[7] For example, the descriptions of the central features of NOS include both philosophical perspectives on science and characteristics inherent to scientific knowledge (epistemology of science), such as the empirical and tentative nature of scientific knowledge and the key distinction between theories and laws, as well as the sociological perspectives on scientific practice, such as social dimensions and cultural embeddedness of science.[8] Even though some NOS research tends to reduce NOS to a few epistemological aspects, the core conceptual framework of STS seems compatible with broader consensual NOS issues, whose enlarged frame embraces much more relevant features and keeps NOS more faithful to its multifaceted and contentious character (Matthews 2012).

The decades of research on the NOS conceptions of students and teachers allow Lederman (1992) to affirm consistently that students and teachers do not have appropriate knowledge about NOS. Research in science education to improve learning and teaching about NOS has largely documented the difficulties associated with developing sound understanding of NOS. The complexity of this task is due to the amount of interacting factors involved that prevent, limit, or facilitate teaching NOS and clarifying the effectiveness of different methods. In spite of the difficulties, it seems that some necessary, though not sufficient, conditions are curriculum development (planning, developing, and assessing) and the effectiveness of teaching in the classroom. The several contexts for developing and teaching NOS used in these studies express the complementary importance of domain-general NOS features and the diversity of domain-specific implementations. Some domain-specific contexts involved in the studies that test the effectiveness of teaching are the following: practical activities (inquiry processes), specific courses on methods and philosophy of science and technology, history of science and technology, techno-scientific issues of social interest, and impregnation of traditional science and technology with NOS contents.

An important part of implementing these contexts is the verification of the effectiveness of a variety of NOS teaching methods, which can be summarized in two basic approaches (Abd-el-Khalick 2012; Lederman 2007):

1. *Implicit teaching:* NOS contents are implicitly inserted into classroom activities, without any further planning or discussion of them, which presumably leads to NOS learning as an automatic by-product of activities.
2. *Explicit instruction:* NOS contents are made explicit in the educational activity (curricular planning and meaningful objectives, content, and evaluation), and clear reflective applications are developed in the classroom through argumentation, development of metacognition, or conceptual change.

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[7] See, for instance, Abd-el-Khalick (2012), Leach et al. (2003), Lederman (2007), Osborne et al. (2003), Sandoval (2005), Tsai and Liu (2005), and Vesterinen et al. (2011).

[8] See, for instance, Abd-El-Khalick (2012), Lederman et al. (2002), and Osborne et al. (2003).

The review of literature on the relative impact of implicit versus explicit approaches towards addressing NOS issues shows that implicit approaches are less effective than explicit reflective approaches (Abd-El-Khalick and Lederman 2000). As an explicit and context-based approach for teaching NOS, the history, sociology, and philosophy of science form the natural setting for discussion, because each of them shows how to build scientific knowledge in the social and historical context (Hodson 2008; Lederman 2007). A specific pedagogical attention to the epistemic and social aspects of inquiry through discursive argumentation activities is also stressed in a recent review of curricular interventions on changing students' NOS conceptions (Deng et al. 2011).

58.4.2 From NOS to NOST

As mentioned earlier, some scholars tend to reduce NOS features especially to philosophical values and epistemological characteristics of scientific knowledge. Although reductionist definitions of NOS could also improve skills, such as distinguishing between good science and bad science as well as the capacity to read and evaluate scientific texts, there is a need for a larger set of skills and attitudes to address science and technology-related issues in a critical way and to reach informed decisions on socioscientific issues impacting our society and the environment. From this wider perspective, it can be argued that there is a need also for a broader conception of NOS encompassing a wider variety of features, such as how science builds, validates, disseminates, and develops knowledge; what values are involved in scientific activities; which are the characteristics of the scientific community; and how science is related to society and culture.[9] Further, even though the roles of social and societal dimensions of science are sometimes cited as central features of NOS, the role of technology is often neglected in most definitions. In order to produce an authentic image of science, there is clearly a need to embrace both the science and technology as complementary aspects of contemporary scientific activity and emphasize the techno-science dimensions of NOS (see, e.g., Tala 2009; Vesterinen et al. 2011).

To tackle these issues, the rich history of the STS movement provides a variety of pluralistic educational models of science and technology, which help students and teachers to answer questions or to critically assess coexisting controversial views, rather than pursuing indoctrination into a particular model of science and technology such as memorizing a couple of uncontroversial tenets about NOS. Even though certain teachers might favor a misbalanced or limited presentation of science, either empiricist or relativist, or avoid questioning on a debatable issue (see Clough 2007), a more pluralistic model which includes several coexisting views of science and technology and their interactions should be provided (see

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[9] See, for instance, Acevedo (2008), Matthews (2012), Vázquez et al. (2004), and Vesterinen et al. (2011).

Matthews 2012). To cover the enormous complexity of techno-scientific systems in contemporary societies, we argue that the concept of NOS should be extended as nature of science and technology (NOST), which would take into better consideration issues such as the ethical and democratic values of science and technology and solving social and ecological problems through human agency and action.

The former reflection does not imply that students become historians, philosophers, or sociologists of science and technology. Rather, understanding NOST through science education has to be developmentally adapted to students and contexts, to attain modest and realistic goals (see Abd-El-Khalick 2012; Matthews 1998). For instance, the students should acknowledge the history of science, the role of the scientific community in the production of scientific knowledge, and some basic features of the philosophy of science, to become competent in informal reasoning on issues at the coupling of science, society, technology, affectivity, ethics, moral development, and civic participation.

58.5 Conclusion

This paper aimed to reflect on the course of implementation of innovative humanistic approaches to school science starting from the leading role of the science-technology-society (STS) movement ahead. It aimed to set up and to follow up the continuities and discontinuities of this evolution through the new emergent currents for teaching and learning science that become associated with the history, philosophy, and sociology of science. Although there are several other slogans and labels for this kind of humanistic science education (see, e.g., Aikenhead 2006), the chosen approaches have been selected because of their most notable influence on school science education.

The leading role of the STS movement is the cornerstone of what has been known as humanistic science education and its many derivatives, such as discussion of socioscientific issues (SSI) and nature of science (NOS). In fact, the six STS currents identified by Pedretti and Nazir (2011) draw quite explicitly on the thesis of the global resemblance among STS, SSI, and NOS approaches. Although it can be argued that STS and the aforementioned research lines (SSI and NOS) are different educational trends, it seems quite obvious too that they all share the importance of developing broad key competencies for scientific and technological literacy and are deeply rooted in the history, philosophy, and sociology of science.

The early distinction between the two fields of science and technology studies provides the inspiration for looking at the clear and direct evolution and connection of STS and NOS approaches. The “science and technology studies” interested in understanding scientific and technological practice and discourse and the “science-technology-society studies” interested in understanding social issues linked to scientific and technological development at some point appeared to be separate projects (see Sismondo 2010). Based on this division, STS and its direct derivates such as STSE and SSI were mainly inspired by research on social issues linked to science and technology. Conversely, NOS was mainly influenced by science and technology studies focused on scientific practice. These two broad fields of science and technology studies have in recent decades blended together. As part of the clearer current understanding on the global interrelatedness of science-technology-society issues, also STS, SSI, and NOS are now being perceived as related and overlapping constructs: STS and SSI approaches include the understanding of NOS features as a central educational objective, and conversely, socioscientific issues are used as an educational context to teach NOS features.

Alternatively it can be argued that if STS and the aforementioned research lines are dominated by the overall continuities among them to such a degree, then they should not deserve different labels. The amount of literature accumulated on each of these areas and the definitions made by their promoters on their unique characteristics and demarcation criteria project an interested image of epistemological differentiation rather than continuity from the original STS (i.e., the promoters of SSI insist on the moral and character education of SSI as a key differential trait from STS). A balanced position on humanistic approaches to science education should recognize the continuities as well as their progress along the differential discontinuities. In spite of the continuities, the rising of the different labels from the original multiform STS proposals has certainly contributed to deeper progress of research by reframing more specific educational problems, such as literacy and scientific competence beyond process skills, contribution to moral education beyond general impact on society, argumentation on facts and evidences beyond critical thinking, and understanding specific consensual issues on NOS beyond generic understanding about science, just to mention some of the most significant milestones of this progress.

The proponents of STS and its more recent derivates have also been active in redefining scientific literacy, which has developed into an umbrella term covering most aims of science education (e.g., DeBoer 2000; Laugksch 2000). Currently all the aforementioned approaches fit under the banner of scientific and technological literacy. For example, Hodson (2009) presents a conceptualization of scientific and technological literacy aligning with the STS efforts to innovate science education by adequately dealing with many challenges of a scientifically and technologically mediated world. Inspired by description of functional competencies of technology by Layton (1993) and competency model of science literacy by Gräber and colleagues (2002), Hodson (2009, p. 15) describes four major elements of scientific and technological literacy as a goal for school science education:

- *Learning science and technology* – acquiring and developing conceptual and theoretical knowledge in science and technology and gaining familiarity with a range of technologies
- *Learning about science and technology* – developing an understanding of the nature, methods, and language of science and technology; appreciation of the history and development of science and technology; awareness of the interactions among science, technology, society, and environment; and sensitivity to the personal, social, economic, environmental, and ethical implications of technologies

- *Doing science and technology* – engaging in and developing expertise in scientific inquiry and problem solving as well as developing competence in tackling "real-world" technological tasks and problems
- *Engaging in sociopolitical action* – acquiring (through guided participation) the capacity and commitment to take appropriate, responsible, and effective action on science-/technology-related matters of social, economic, environmental, and moral-ethical concern and the willingness to undertake roles and responsibilities in shaping public policy related to scientific and technological developments at local, regional, national, and/or global levels

The STS movement has been instrumental in setting up a basic shift of understanding of the term scientific literacy towards scientific citizenship and its association with science for all. New conceptualizations of scientific and technological literacy, such as the one presented above, demand that science teaching can no longer be bound to the transmission of traditional scientific and technological knowledge aimed to prepare scientists and engineers, which has been the indisputable and perennial aim of science education all over the world. Science education should go beyond science facts and laws to get a more holistic and useful approach for citizens, most of whom do become neither scientists nor science workers. Literacy for all assumed the original concern of STS movement to include all students into the culture of science and technology, no matter the minority they belong to, through improving their interest and attitudes to science, in order for them to become better citizens and better prepared to participate in society. It is argued that science education simply cannot stick to the scientific knowledge and the process of producing such knowledge, but the goals and capacities to be developed should have a more holistic approach and a genuine social relevance, including ethical and democratic values (Holbrook 1998). Thus, the STS proposals have also evolved to improve their contribution to science education, not just drawn to acknowledge the pitfalls but also to attain new educational challenges (such as scientific and technological literacy for all) in new educational settings and societal contexts (information, communication, and risk societies).

The STS movement and its conceptual variations originated from and have been influenced by interdisciplinary science and technology studies in higher education as well as environmental and civil rights movements. These roots are all but forgotten in the current humanistic perspectives such as NOS and SSI. New research on history, philosophy, and sociology of science still informs research and practices on science education, and the capacity and commitment to engage in sociopolitical action on matters of social and environmental concern are increasingly seen as the key competencies developed through science education (see, e.g., Hodson 2009). The humanistic perspective challenges traditional science education in at least four ways:

1. *The switch of focus from "science for scientists" to "science for all" (from Vision I to Vision II):* Science education must be inclusive, that is, committed to the aim that all students (not only those aiming to be scientists) should understand contents "of" science (concepts) and concepts "about" science (NOS). Science

education should enculturate students into their local, national, and global communities, rather than into scientific disciplines.

2. *Focus on the relevance of learning:* To achieve the education that excludes no one and to produce significant learning that is useful for students' everyday life, science education is expected to be interesting and relevant. Science education should thus be context-driven and student-centered.
3. *Focus on the additional key competencies in science and technology:* The focus of science education cannot be solely on knowledge, skills and characteristics demanded of scientists, but rather on the knowledge, skills and characteristics demanded of general citizens. Such competencies include, but are not limited to, the following skills: high order cognitive abilities (argumentation, analyzing, synthesizing and evaluating information), informed decision making, communicating and discussing openly ideas and facts, and designing and developing projects.
4. *Focus on the history, philosophy, and sociology of science contents:* For example, the task of making informed decisions on socioscientific issues demands some knowledge "about" science. The history, philosophy, and sociology of science can be used either as core curriculum content or as the context that surrounds disciplinary learning activities in science.

The current concern for effective and evidence-based teaching and learning is perhaps the most practical drive for connecting history, philosophy, and sociology of science content and curricular developments in classrooms. Although the number of evaluative studies is quite scarce within the STS movement proper, as the study of Bennett and colleagues (2007) evidences, the evaluative studies available on scientific literacy (e.g., OECD's PISA project), NOS (e.g., Lederman 2007), or SSI (e.g., Sadler 2011) are essential to broaden our view. Evaluations of humanistic approaches in science education point out that success in this field requires some basic conditions. Most of the current literature is unanimous in acknowledging that developmental, explicit, and reflective teaching is a necessary condition to successful learning, which in turn must be supported by detailed curricular planning.[10] These plans should involve explicit objectives, activities, and assessment and many reflective activities within classroom implementation where students are given opportunities to consider, discuss, construct arguments, and consolidate their understandings on broad features of science.

To meet the wide variability of demands from primary education to college education students, curricular planning should also acknowledge a developmental perspective. For instance, the controversial and interrelated character of the history, philosophy, and sociology of science issues suggests that decisions on sequencing issues across grades are not obvious. In spite of this, the developmental perspective has been scarcely discussed in NOS and SSI research, perhaps supposing implicitly that teachers are able to adequately cope with it while transposing their practical

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[10] See Abd-el-Khalick (2012), Bennett et al. (2007), Lederman (2007), Matthews (2012), Sadler (2011), and Vesterinen and Aksela (2012).

knowledge in science teaching to teach humanistic content. Thus, the previous prescriptions and conditions to achieve effective teaching and learning need to be complemented with accurate developmental sequencing of issues and activities (see, e.g., Abd-el-Khalick 2012).

Summing up, this chapter traces a journey through humanistic perspectives in science education from STS and scientific literacy movements to the current SSI and NOS movements, influenced by and influencing the various conceptualizations and reconceptualizations of scientific and technological literacy. Along this journey some might perceive a kind of reductionism, as the wide variety of historical, philosophical, or sociological controversial issues in science and technology education, which are typical of humanistic approaches (see Aikenhead and Ryan 1992), have been progressively focused on a much more specific and limited list of features. For instance, much of the research and teaching experiences on SSI issues focuses on current social controversies, thus relegating to a corner the many past historical controversies, which are also essential to sound training in science. Further, much research and teaching on NOS focus on seven issues elaborated by Lederman and his colleagues (e.g., Lederman 1992, Lederman et al. 2002), thus relegating out of the scope of scientific literacy wider visions of NOS and many NOS issues. This reductionism could help researchers to better demarcate the field of study, while in education this effort might be justified on the basis of meeting the students' needs, for example, in the selection and choice of curriculum issues that could better fit the diverse populations of students (simpler pedagogical transposition, best modest goals, students' age and interests, etc.). In the long run, however, this reduction somewhat weakens the richness of the original historical, philosophical, or sociological roots of humanistic approaches to science education, and claims for overcoming this reductionist state of affairs have already been put forward (see Matthews 2012).

Coinciding with the planned school science reforms, developed and implemented in many countries over recent years, the international debate over humanistic perspectives in higher education has also been revitalized. According to Sjöström (2008), there is a need for taking into account the societal and ethical dimensions of scientific practice and taking part in public discussion about the discipline by practicing scientists; in turn, this involves a need for more emphasis on Vision II-like approaches also in the education of future scientists. Krageskov Eriksen (2002) argues that with a humanistic perspective guiding the educational planning, scientists and engineers capable of critically considering the premises of the system, "the rules of the game" – not just skilled players – could be the intent of higher education. She argues for the need of three kinds of knowledge in tertiary science education: (1) "ontological" scientific knowledge, i.e., scientific facts and theories; (2) "epistemological" knowledge, i.e., philosophical and sociological perspectives on the scientific practice; and (3) "ethical" knowledge, i.e., reflection on the role of science and science education in society. The humanistic perspective originating from the engineering colleges and academic science-technology-society programs seems to be returning back to colleges and universities via the STS school science movement.

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Chapter 59

Cultural Studies in Science Education: Philosophical Considerations

Christine L. McCarthy

59.1 Cultural Studies of Science

Contemporary science education is considered by many to be in need of a fundamental re-structuring, based upon a fundamental re-conceptualization of science. Work in the field of cultural studies of science education attempts to provide the basis for this revision. Prominent themes that are current in the CSSE literature can be traced to a number of classic mid-twentieth-century works in the philosophy and sociology of science. In this section five foundational themes and their sources are examined.

59.1.1 The Sociological Study of Science: Merton

It is uncontroversial that the activities of scientific inquiry are human activities, invariably occurring in a social context. The social context necessarily affects the historical course of scientific inquiry, and the social world is itself affected by the developing science. Sociological studies of science have examined the activities of practicing scientists and explicated the interactive relationship of science in society. Beginning in the 1930s, Robert Merton advanced the sociology of science by conceiving of science as itself a social institution. Merton's work focused on the social structure of science, the relations and interactions internal to, and, perhaps definitive of, the institution of science. Merton, often considered to be the founding father of the sociology of science, argued that science cannot be developed and cannot be maintained, unless certain cultural conditions obtain in the society (1938/1973, p. 254). Absent the favorable cultural conditions, hostility toward science can be expected to occur.

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Merton developed a conception of the ethos of scientific inquiry. This ethos is an "…affectively toned complex of values and norms which is held to be binding on the scientist…expressed in the form of prescriptions, proscriptions, preferences, and permissions" (Merton 1973, p. 269). This ethos is maintained and transmitted by the institutional structure of science. It is possible that some practices which occur in the context of science and which are taken to be scientific actually depart from the values and norms of science. To the extent that they do, nonscientific or pseudoscientific work is being produced under the guise of science. Science in such a case would suffer a collapse from within.

Merton also observed that science can be attacked from without: "science is not immune from attack, restraint, and repression" (p. 267) and "[l]ocal contagions of anti-intellectualism threaten to become epidemic" (p. 267). Advanced scientific work leads to the development of complex theories about the world[1] that cannot be understood without extensive study. Such theories are largely unintelligible to nonscientists. This incomprehension undermines cultural support for science and leaves the majority of persons "ripe for new mysticisms clothed in apparently scientific jargon" (Merton 1938/1973, p. 264). In addition, the organized and continual skepticism characteristic of science will at times threaten the interests of entrenched power holders and/or cast doubt on the truth of deeply cherished nonscientific beliefs. Science is then likely to be threatened by an organized social backlash against it.

Merton identified four institutional imperatives that constitute the ethos necessary for science. The first is an objective *universalism*. "[T]ruth-claims, whatever their source, are to be subjected to *pre-established impersonal criteria*: consonant with observation and with previously confirmed knowledge" (1942/1973, p. 270, emphasis in original). None of the personal or social attributes of the scientist are to enter into the assessment of the truth claims. Merton's universalism rests upon the objectivity of the world itself, the object of scientific inquiry. In science, Merton holds, "…[o]bjectivity precludes particularism. The circumstance that scientifically verified formulations refer…to objective sequences and correlations militates against all efforts to impose particularistic criteria of validity" (1942/1973, p. 270).

Merton explicitly rejects social, cultural, and/or racial particularism, holding that "[e]thnocentrism is not compatible with universalism" (p. 271). While accepting that the historical course of development of science is influenced by its cultural context, Merton rejects the notion that scientific knowledge could have a particular cultural, "national," or class-based content. It is possible, Merton maintains, to compare and assess the merits of inconsistent competing claims to knowledge that might arise in different cultures.

> …[T]he cultural context in any given nation or society may predispose scientists to focus on certain problems….But this is basically different from the second issue: the criteria of validity of claims to scientific knowledge are not matters of national taste and culture. Sooner or later, competing claims to validity are settled by universalistic criteria. (Merton 1942/1973, p. 271, n. 6)

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[1] The term "the world" herein refers to the set of all entities and dynamic interactions that exist and occur and is synonymous with nature or reality, or simply "what is."

Merton's second institutional imperative in the ethos of science he terms *communism*. This is the assertion that the knowledge acquired by scientific inquiry belongs rightfully to the human community as a whole. "The substantive findings of science are a product of social collaboration and are assigned to the community. They constitute a common heritage…" (1942/1973, p. 273). Merton emphasizes that communal investigation is a necessary aspect of scientific inquiry.

The third imperative is *disinterestedness*. Merton remarks upon "[t]he virtual absence of fraud in the annals of science…" (p. 276) and attributes this honesty not to a superior moral integrity of individual scientists, but rather to the institutional structure of science. Inquiry, to count as scientific, must be subjected to the rigorous scrutiny of the community of qualified scientific peers. Given that scientific theories refer to an objective world, it is likely that peer scrutiny will eventually expose whatever fraudulent or incompetent practices might occur. It is when the institutional structure of science breaks down, Merton writes, that "[f]raud, chicane and irresponsible claims (quackery)" (p. 277) proliferate. "The abuse of expert authority and the creation of pseudo-sciences are called into play when the structure of control exercised by qualified compeers is rendered ineffectual" (p. 277).

The fourth institutional imperative is *organized skepticism*, which Merton considers to be "…both a methodological and an institutional mandate" (p. 277). The commitment to skepticism gives rise to conflict between the institution of science and other social institutions, e.g., religious, economic, and political institutions, when such social institutions demand an uncritical respect for and acceptance of certain doctrines. A revolt against science by the culturally powerful may be launched in response.

Merton's sociological research provides a clarification of the social structure of scientific inquiry and its relations to the wider society. Merton's approach involves empirical study of the practices and norms of the social activity of scientific inquiry. His findings go beyond simple description of characteristics found in scientific practice, to an analysis of which characteristics are necessary and definitive. Merton's approach has been largely replaced in contemporary cultural studies of science by a method of cultural criticism.

59.1.2 The Incommensurability of Scientific Theories: Kuhn

Kuhn's (1962) work, *The Structure of Scientific Revolutions,* cast doubt on the belief that the history of science has been one of cumulative progress in scientific knowledge of the dynamics of the world. Kuhn interprets the history of science as a series of revolutions that bring about fairly sudden and fundamental changes of scientific views of nature. These changes Kuhn calls paradigm shifts, defining a paradigm as a set of "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners" (p. viii).

In Kuhn's view, as long as a particular paradigm is in place, a calm period of normal scientific work occurs. The routine work eventually exposes anomalies, findings that don't fit within the current paradigm, which creates a crisis that can be resolved only by revolutionary change in the current paradigm. Following a paradigm shift, the world is understood in fundamentally different ways. Previously accepted theoretical entities are eliminated from the new conception of reality, and new entities, with new interactive dynamics, take their place. So fundamental is the shift in worldview that the theories belonging to the different paradigms, in Kuhn's view, are incommensurable – the terms in the old theory cannot be translated into the language of the new theory. It would seem to follow that there is no legitimate way to rationally assess the relative merits of the old and new theories or of any competing theories. If this is so, change in accepted theory would have to be driven largely by extrascientific factors that function causally, but irrationally, to determine individual and social subjective states of belief.

Kuhn's work contributed to a fundamental reevaluation of the conception of science, of scientific inquiry, and of scientific knowledge. Kuhn noted that theories about the world that are now judged to be false were once considered to be well justified and were counted as knowledge. He concluded that "…once current views of nature were, as a whole, neither less scientific nor more the product of human idiosyncrasy than those current today" (p. 2).

Kuhn appears to argue that if we now dismiss those widely accepted ancient beliefs about the world as mere myths, we should consider the currently accepted beliefs arising from contemporary scientific inquiry to be equally mythic. Given that the vast majority of belief systems in the past have been judged to be mostly wrong, it appears to follow that the majority of our current beliefs are also likely to be mostly wrong. This line of reasoning is sometimes called the pessimistic induction, pessimistic because it suggests that science proceeds by substituting one wrong system for another, without actually progressing toward true belief.

Kuhn's (1962) analysis is often taken as a repudiation of the possibility of rational bases for theory change. Yet Kuhn's analysis rests on the observation that crises of belief arise because new findings of scientific inquiry cannot be understood given the current explanatory theory. A problem is thus set, and a new theory is sought which will better explain the new observations and the old. Proposed theories are comparatively assessed and judged by their ability to resolve the current theoretical problem. The continued process of theoretical crisis and theoretical resolution of the crisis should be expected to lead to gradual improvement in the theoretical understanding of the world. The history of science should lead to optimism regarding the increasing verisimilitude, or nearness to truth, of scientific knowledge, despite any non-translatability of successive theories. The optimistic view of the growth of scientific knowledge is often dismissed in the cultural studies literature as naïve or as a piece of propaganda deliberately deployed in a political struggle for power and domination.

Kuhn's incommensurability thesis appears to support the belief that concurrent but inconsistent cultural systems of belief about the world are simply different and incommensurable paradigms. On this view, it is thought that no culturally neutral grounds can exist that would allow for reasoned choice among different cultural belief systems. Kuhn's work thus is taken to support the view, prominent in cultural studies of science, that there are no legitimate grounds for considering modern science to be of a special cognitive significance. Scientific knowledge is to be considered merely one system of belief among many others that are equally legitimate.

It is ironic, then, that Kuhn, in 1977, develops a set of five criteria for theory choice in science. The first is accuracy of fit to nature: the "consequences deducible from a theory should be in demonstrated agreement with the results of existing experiments and observations" (1988, p. 278). The second is consistency: a scientific theory should "…be consistent, not only internally or with itself, but also with other currently accepted theories applicable to related aspects of nature" (p. 278). The third is broad scope: a theory's "consequences should extend far beyond the particular observations, laws, or subtheories it was initially designed to explain" (p. 278). Fourth, a theory should be "simple, bringing order to phenomena…" (p. 278). Fifth, it should be fruitful: it should "disclose new phenomena or previously unnoted relationships" (p. 278). These five criteria, Kuhn states, "are all standard criteria for evaluating the adequacy of a theory…they provide the shared basis for theory choice" (p. 278). So, for Kuhn, the strict non-translatability, i.e., the incommensurability, of competing theories identified in his 1962 work does not in fact prevent comparative evaluation of the merits of the competing theories.

Kuhn does argue in 1977 that these and other criteria of theory choice cannot be fashioned into a complete algorithmic decision procedure, binding on all members of a scientific community. Judgment is always necessary in evaluation, and individuals who come to minority conclusions are not ipso facto unscientific. Subjective considerations might not be wholly expunged when individuals make evaluative judgments of the merits of competing theories. But there are, in Kuhn's view, rational criteria for judgment, and an open communal and critical discussion of differing individual judgments promotes judgment on rational criteria. "The criteria of choice…function not as rules, which determine choice, but as values, which influence it" (p. 285).

It is Kuhn's earlier work that has been incorporated into the foundations of the CSSE literature.

59.1.3 Cultural Relativism and Science: Barnes and Bloor

Sociologists Barnes and Bloor develop a relativistic theory of knowledge, which they claim is required by "…the scientific understanding of forms of knowledge" (1982/1994, p. 21). They make three claims. The first two are uncontroversial: "(i)…beliefs on a certain topic vary, and…(ii) which of these beliefs is found in a given context depends on, or is relative to, the circumstances of the users" (p. 22). Their third claim, the "equivalence postulate," however, is problematic. The equivalence postulate states that the truth status of a belief is irrelevant to the explanation of the "causes of credibility" of the belief. This may be true, in many cases; it is common to observe instances of confident belief about the world that would later prove false. But the observation is about the empirical cause of a subjective state of mind of a believing creature. This is not relevant to a theory of knowledge, which poses conceptual and normative questions, e.g., whether or not a particular confident state of belief ought to be counted as knowledge.

Barnes and Bloor, though, stipulate that they will be using the term "knowledge" in a specific way: "We refer to any collectively accepted system of belief as 'knowledge'" (p. 22, n. 5). This stipulation is problematic, however. To believe a proposition is simply to accept that the proposition is true and to be prepared to act as if the proposition is true. But, the subjective belief that a proposition is true, even when collective, itself provides no evidence about the actual truth or falsity of the proposition.

Barnes and Bloor cope with this difficulty by eliminating from their conception of knowledge any considerations of truth. There will be no consideration of the relative merit of different systems of collective beliefs in terms of truth, or of "nearness to truth," or *verisimilitude*.[2] Barnes and Bloor see no problem in their omission of the concept of truth, because they take use of the words "true" and "false" to merely "provide the idiom" through which individuals express their natural subjective preferences for their own cultural beliefs. Barnes and Bloor continue to use the word "knowledge," but their claims about knowledge must be understood to be claims only about collectively accepted systems of belief.

In the absence of concern about truth, any comparative assessment of the merits of different bodies of belief is seriously restricted. Despite Barnes and Bloor's redefinition of the term "knowledge," there remains need for a term that refers to systems of belief that are thought, for good reasons, to be true or at least more nearly true than competing systems. The term "knowledge" has long served this purpose in ordinary English usage.

This suggests another problem with the equivalence postulate. Finding a causal explanation of an individual or collective state of belief is not the same thing as finding *good reasons for* the state of belief. After one has reached a well-grounded explanation about *how* a particular belief was caused, it is still sensible to ask whether it is a good thing that the belief was so caused. Barnes and Bloor, however, collapse the important distinction between causes of believing and reasons for believing and assert that discovery of the causes of belief is identical to discovering reasons for the belief. Having collapsed the distinction, they maintain that the sociology of knowledge is not to be "…confined to causes *rather than* 'evidencing reasons'. Its concern is precisely with causes *as* 'evidencing reasons'" (p. 29).

Seeking causal explanations for states of affairs, seeking the conditions of occurrence of a state of affairs, is a central and legitimate aim of scientific inquiry, and scientific inquiry into the empirical causes of collective belief is interesting and important. But sociological inquiry into the facts of belief acquisition is not an inquiry into acquisition of knowledge, unless knowledge is conceived in the limited *subjective* sense of individual and/or collective belief. Further considerations regarding the concept of knowledge will be taken up in Part 3.

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[2] Popper's term; see Sect. 59.3.3 for further discussion.

59.1.4 Science as Cultural Tyranny: Feyerabend

Feyerabend, in *How to defend society against science*, develops a broad critique of science as a human endeavor. He writes in support of the wholesale rejection of modern science, on the grounds that achievement of true belief limits freedom of thought:

> [m]y criticism of modern science is that it inhibits freedom of thought. If the reason is that it [modern science] has found the truth and now follows it, then I would say that there are better things than first finding, and then following such a monster. (Feyerabend 1974/1988, p. 37)

Feyerabend writes that scientific knowledge is merely an ideology, no different from the ideology of the Church or of Marxism. He rejects the notion that scientific inquiry is a distinctive mode of activity: "…there is no 'scientific methodology' that can distinguish science from the other ideologies. *Science is just one of the many ideologies that propel society and it should be treated as such…*" (p. 40, emphasis in original).

Feyerabend notes that there are practical educational consequences of his position and approves, writing: "Three cheers to the fundamentalists in California who succeeded in having a dogmatic formulation of the theory of evolution removed from the text books, and an account of Genesis included" (p. 41). It appears that, in Feyerabend's view, maximal freedom of choice in believing is the primary cognitive value to be achieved; having a well-warranted body of knowledge about the world is not a comparable value.

The animus against science that Feyerabend evinces in his writing seems based on a conception of the negative effect an ideology of science would have on humanity. In "Dehumanizing Humans," he speaks of the look on the face of a friend, in which, he says, the whole relationship is written. He asserts that a scientific worldview would devalue this important, albeit subjective, human experience. "This look is not an objective fact…it is not 'scientifically important' and if science takes over, not socially important either" (1996, p. 95).

In "The Disunity of Science," Feyerabend asserts that the objective ontology of materialism that grounds science forces human beings to accept the reality of a world without subjective human experiences. Classical physicists, he writes, "distinguished between the objective world of scientific laws – and this world is without change – and the subjective world of our experiences. They ascribed reality to the former and regarded the latter as an illusion" (1996, p. 39). Philosophers, certainly, have sometimes made this move, and Feyerabend's objection to it are well grounded. As long as creatures having a requisite type of complexity really exist, as they clearly do, subjective states of affairs – feelings, desires, hopes, and beliefs – will also really exist, as states of those creatures. It is possible, however, to reject problematic philosophical theses associated with science without rejecting scientific inquiry in toto.

Yet Feyerabend's belief that science itself is hostile to the most important facets of human experience has become a common one. If scientific inquiry were in fact hostile to human experience and to human values, purposes, and emotions, then a passionate antipathy to science would make sense. But neither scientific inquiry nor scientific knowledge requires a denial of the fact of the qualitative, subjective experiences of human life. Far from denying those experiences, scientific inquiry, in leading to knowledge of the dynamic relations in the world, promotes the human quest for valued qualitative experiences.

Preston (2000) quotes Feyerabend on the disunity of science, its lack of a characteristic epistemology:

> Science is not one thing, it is many; and its plurality is not coherent, it is full of conflict. There are empiricists who stick to phenomena and despise flights of fancy, there are researchers who artfully combine abstract ideas and puzzling facts, and there are storytellers who don't give a damn about the details of the evidence. They all have a place in science. (Feyerabend 1992, p. 6)

The conception of science as all inclusive, so that even storytellers who don't give a damn about evidence are to be counted as practitioners of science, is evident in much of the CSSE literature.

It may be that Feyerabend was not entirely serious in his assertions about science. The essays collected in Preston's *The worst enemy of science?* provide insight into Feyerabend's scholarly intentions, and philosophers of science who knew Feyerabend personally write that he was intentionally provocative and extreme in his assertions about science.[3] But, whatever his intentions, Feyerabend's writings are often taken seriously and at face value. The effect of his writings has been to provide support to contemporary critiques of, and rejection of, modern science as the mode of inquiry that is best able to lead to knowledge of the world.

59.1.5 Science as Cultural Domination: Harding

Harding's feminist work is widely cited in cultural studies in science education literature and exemplifies certain philosophical issues central to current critiques of science (e.g., 1986; 1998).[4] Harding describes her position as a *standpoint* theory, one that values the standpoints of those who are *other* with respect to some cultural milieu. The others with respect to science include women, nonwhite ethnic/racial groups, non-European cultures, and cultures from the past. Taking on others' standpoints, Harding maintains, enables the detection of culturally based distortions in knowledge. Harding's acknowledgement of the possibility of error in belief, and of correction of that error by critical communal discourse, is significant. In accepting this, Harding appears to accept that there is an objective order in nature, i.e., that there are regular patterns of events in nature and that such patterns can be recognized, if an inquiry process properly structured to promote unbiased comparative assessment of theories is developed. In this respect, Harding's position would appear to be close to that of Merton.

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[3] See also Horgan (1993).

[4] See Grasswick (2011) for an overview of feminist work in the philosophy of science.

Yet, contra Merton, Harding argues that the claims of Western modern science to universality and objectivity should be rejected as illusions. Harding argues that all theories about the regular patterns in nature are social constructs and that all social constructs are strongly influenced by social, cultural factors and by political agendas. Given this, Harding concludes that scientific theories are neither objectively determined nor politically neutral. The bodies of collectively accepted belief developed in different cultures, which Harding takes to constitute the culture's science, should be expected to diverge in both method and content. The problem here is that Harding's conclusion relies on an assumption that any degree of influence on science by social factors negates the claim of science to objectivity. But, absolute objectivity need not be conceptually required. A greater degree of objectivity is the value to be sought in scientific inquiry. The institutional structure and norms of scientific inquiry support the goal of achieving greater objectivity.

Harding maintains that all theories about the world are underdetermined by empirical evidence. She takes this to mean that different and mutually inconsistent theories can be constructed, all of which will be equally consistent with all possible empirical evidence. The best that any scientific theory can achieve, then, is empirical adequacy, i.e., consistency with observational data. "Many socially constituted theories about nature can be *consistent* with nature's order, but none are uniquely *congruent* with it; none uniquely correspond[s] to it" (1998, p. 176).

Harding further maintains that it is impossible to comparatively evaluate different empirically adequate theories, because it is impossible to acquire empirical evidence that would definitively rule out some of the empirically adequate theories. Absent the possibility of disconfirmation through scientific inquiry, in Harding's view, as in Kuhn's (1962) work, it can only be social, cultural, political, and historical factors that determine which theories about the world come to be accepted in a culture.

But, Harding does not take into account the commitment in scientific inquiry to an ongoing search for new evidence, the study of previously unconsidered situations, that will, in creating Kuhnian crises, allow for comparative evaluation of competing theories. The fact that, at an early stage of scientific inquiry, competing theories are equally adequate to current observational evidence does not entail that they will always be. The existence of two or more competing theories constitutes an intellectual problem for the scientific community and encourages intensive scientific inquiry to resolve the problem.

Harding holds that, in practice, persons in positions of social power will make the decisions that establish culturally specific belief systems.[5] The resultant belief system, unsurprisingly, will serve to maintain the existing social power relations. Social power dynamics determine what research projects will be permitted and which will be funded. Power dynamics also operate within the scientific community, determining which observations, and which theories, will be considered authoritative in the scientific community. On Harding's view, it is in principle impossible that continued scientific inquiry might lead to results that would *objectively* decide a scientific issue.

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[5] See Oreskes and Conway (2010) and Wagner and Steinzor (2006).

Dominance relations occur at the level of individuals, and of social strata, and also at the intercultural level. Harding observes that "Western" culture is currently globally dominant and takes this geopolitical dominance to explain why "Western" scientific theories are currently intellectually dominant. Modern scientific methods of inquiry, and the scientifically generated body of knowledge, on this view, have been imposed on other cultures, in the face of their resistance.

Harding claims not to reject in toto what she calls the "European scientific and epistemological legacy" (p. 125). She does, however, argue that European science should be updated and means by this that it should be reconceptualized as simply one local knowledge system among many others, all of which are to be conceived as of equal intellectual value.

Harding accepts that the theories resulting from scientific inquiry "may well 'work' in the sense of enabling prediction and control" (p. 132), but she does not believe that "working" provides evidence of the truth, or of the nearness to truth, of scientific theories. Harding maintains that quite different and inconsistent systems of knowledge can provide similar levels of prediction and control. She writes that "…the regularities of nature …may be explained in ways permitting extensive(though not identical) prediction and control within radically different and even conflicting, culturally local, explanatory models" (p. 132). Harding's examples, though, serve only to cast doubt on the general claim. She asserts, for example, that "[f]armers in radically different cultures can predict equally well a large range of weather patterns and their effects, just as health care workers in these cultures can predict when illness will occur and how to cure it" (p. 133).

Yet there is abundant evidence that Harding's claim about the equivalent predictive power of scientific and nonscientific belief systems is false. For example, contra Harding, predicting with any significant accuracy the path of a tornado, or a hurricane, requires the instruments of modern science. Losing the weather satellites we currently rely on would destroy the predictive advantages we currently enjoy, wherever such technology is employed. Reliance on alternative, nonscientifically warranted beliefs about health care is likely to be ineffective, except for its placebo effects.[6] While it is possible that some aspects of some alternative health care might be effective, there are no good reasons to accept any such claim in the absence of a rigorous scientific testing of the claim. It is indisputable that nonscientific peoples have developed practices that provide some measure of success in dealing with some problem situations – the fact of survival over time is evidence of this. But organized scientific inquiry such as Merton describes has led to a body of knowledge that permits successful practice in vastly more situations.

Harding writes that it was once possible to naively imagine that scientific inquiry provided a means to achieve or approach true beliefs about the world. "When the ideal results of research could be assumed to be socially neutral, truth or truth-approaching could appear to be a reasonable way to conceptualize the relationship of our best knowledge claims to the natural and social world" (p. 143). But Harding maintains that once the operations of scientific inquiry are understood to be

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[6] See Bausell (2007) and Singh and Ernst (2008).

dominated by extrascientific influences, as she argues they are, the notion that scientific inquiry can lead to true beliefs, or truth-approaching beliefs, will be discarded. Like Feyerabend, Harding finds all truth claims to be inimical to social discourse. “Truth claims are a way of closing down discussion, of ending critical dialogue, of invoking authoritarian standards” (Harding, p. 145). Rather apocalyptically, Harding asserts “The achievement of truth would mark not only the end of science, but also of history” (p. 145).

But, contra Harding, even the best of scientific theories are not taken, by scientists, to have been absolutely proven to be true. The concept of truth, understood as correspondence of theory to reality, is a regulative ideal in scientific inquiry. But it is well understood within the scientific community that scientific inquiry is an ongoing process of appraisal. A scientific theory, when accepted, is always accepted tentatively, as the best theory to date, pending further inquiry that may falsify it. Nevertheless, a theory may have such strong warrant that it is judged unlikely to be falsified.[7]

Harding’s position has many internal tensions. An orderly and objective reality is accepted, but to develop a body of objective knowledge of reality, involving beliefs that approach truth, is considered impossible. The concept of a universal[8] body of knowledge is replaced by the concept of discrete local knowledges, conceived in the fashion of Barnes and Bloor as collectively accepted bodies of belief. Claims to truth are considered to be means to achieve power or means to destroy free social discourse. The problem with “Western modern science” is taken to be that this mode of inquiry is *as incapable* of delivering a body of objective knowledge as any other mode of inquiry. The claims of science to do so Harding considers to be part of the efforts of the scientific community to achieve cultural domination. Conceiving the problem as one of cultural domination, Harding’s solution seems to be to expose the deceptive nature of modern science and to promote acceptance of the legitimacy of whatever culturally specific belief system is found to be appealing. These positions figure prominently in the CSSE literature. Much less prominent have been the detailed criticisms levelled at Harding’s position by prominent philosophers of science, many of them feminists.[9]

59.2 Cultural Studies of Science Education

Work in the cultural studies of science field lays the foundation for contemporary cultural studies of science education [CSSE]. The advent in 2006 of the journal *Cultural Studies in Science Education* is a significant development. Editors Roth

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[7] See discussion of Popper, Sect. 59.3.3.

[8] Universal claims are those that apply *to the interaction in question* wherever and whenever that interaction occurs.

[9] Koertge argues that feminist epistemology “…stands in a sharply antithetical relationship to the core values of science” (1996, p. 416). See also Haack (2003) and Pinnick (2005 and 2008).

and Tobin introduce the journal in this way: "The journal encourages empirical and non-empirical research that explores science and science education as forms of culture….A requisite for all published articles is…an explicit and appropriate connection with and immersion in cultural studies" (Roth and Tobin 2006, p. 1). The editors note that the journal will include "…OP-ED pieces that present ideas radically departing from oppressive, hegemonic norms" (2006, p. 2).

It is clear from this introduction that the journal is to be intellectually selective, publishing only work that conforms to the politically and socially based critique of science explicitly established as the norm for the journal. Paradoxically, it appears that this is itself an establishment of an alternative norm that is oppressive and hegemonic, albeit on a local scale.

Work in the field of cultural studies in science education is diverse in some respects. Many studies focus on pedagogical practice, interpreting the particular needs of culturally diverse students and proposing means by which the science educator can meet those needs. Philosophical conceptions of the nature of science, reality, knowledge, and truth are explicitly addressed in some studies. A particular set of positions on these issues, consonant with the positions generally developed in the CSS literature, is an explicit expectation in CSSE literature.[10] In this section I examine selected works in the CSSE literature that exemplify fundamental philosophical commitments in the field.

59.2.1 Pedagogical Practice

Elmesky (2011) provides an example of the pedagogical focus in the field. Elmesky notes that culturally diverse students bring with them "…heterogeneous cultural ways of being …that would be typically considered as unscientific …" (2011, p. 54). Elmesky argues that the teacher ought to incorporate the students' cultural ways of being into the study of science. Taking marginalized African American students to constitute a culturally distinct group, and taking rap music to be one of their cultural ways of being, Elmesky incorporates the creation and performance of rap music into the science classroom. Elmesky provides the following rap, created by the students, as an example of culturally relevant pedagogy:

> People depend on sound to get us around almost everyday we sometimes hate it but then we love it especially when we play even the blind it helps them to find a way to see in mind sound makes vibrations which makes equations so take advantage of this information. (Elmesky 2011, p. 65)

Elmesky states with approval that the rap recognizes that sound travels through vibrations and that the phenomenon can be symbolically represented through equations. Elmesky does not provide any evidence that the exercise has helped students

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[10] See also Roth and Tobin (2009).

acquire a scientific understanding of the nature of sound. Elmesky instead justifies[11] the incorporation of rapping in the science classroom as a matter of social justice, as a repudiation of the cultural domination based on class and race that she takes to be inherent in science.[12]

Elmesky's account of the enthusiasm of the students suggests that the time given to rapping may serve a positive pedagogic purpose. It appears to permit a relaxed interlude of simple fun that allows the students to return refreshed to the cognitively demanding work of learning science. But Elmesky does not conceive the rapping interlude in this way. The exercise is said to provide the marginalized students to be themselves; it overturns "…the ideologies of the dominant race and class [that] continue to govern what content is taught as well as the frameworks for pedagogical approaches to instruction" (2011, p. 54).

Elmesky does not consider the possibility that a disservice is done to the culturally marginalized students if they end up with a less rigorous, less thorough, instruction in science than culturally mainstream students. Social justice in education requires that the same high quality of instruction be provided to all students, regardless of social or economic status, or unwarranted assumptions of culturally based limitations in capacity to learn. Contra Elmesky, pedagogical methods in science education should be justified by reference to their effects on the acquisition of scientific knowledge, if social justice in education is part of the educational goal.

Meyer and Crawford's "Teaching science as a cultural way of knowing" provides another example of cultural studies work focused on pedagogical practice. The culturally diverse students in this study are Latino, African American, Native American, and English language learning students. Consistent with both Merton (1942) and Roth (2008), Meyer and Crawford conceive of science as a culture having its own rules and operations, "…a dynamic and negotiated way of knowing that is practiced by a particular community…" (2011, p. 530).

Like Harding, Meyer and Crawford regard the scientific way of knowing as just one way of knowing, among many other different but equally legitimate culturally specific ways of knowing. Scientific inquiry, they write "…is implicated in Western ways of knowing…[which is]…an already accepted cultural norm for many mainstream students" (p. 535). Meyer and Crawford state that "[w]ithout culturally relevant instructional practices aimed toward facilitating student border crossing… science instruction incurs a form of symbolic violence, where one way of knowing dominates and seeks to replace others" (p. 532).

There are good reasons to doubt that the everyday cognitive habits of *any* student are well aligned with the norms of scientific inquiry, when he or she begins to study science. The norms of scientific inquiry make it a decidedly unnatural way of thinking, which not only must be learned but takes considerable effort to learn.[13] Yet it is the commitment, in science, to continual skepticism toward currently accepted theories

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[11] The term "to justify" here means "to give good reasons for" a proposition, belief, or practice and does not imply demonstrative proof.

[12] See also Emdin (2009).

[13] See also Wolpert (1992) and Cromer (1993).

that makes scientific inquiry especially well suited to contribute to the growth of the body of scientific knowledge. Nonscientific ways of thinking, lacking the commitment to organized skepticism, place value on a non-changing body of belief, maintained by indirect cultural norms that prohibit skepticism and by direct coercive force when necessary.

There is no good reason to conclude that students of certain ethnicities or students whose first language is not English would be drawn innately to nonscientific ways of thinking or would experience greater difficulty in learning science than Caucasian speakers of English. The educational challenge, for all students, is to find pedagogical methods that lead to an understanding of contemporary scientific knowledge, at least sufficient to support rational participation in social policy determination, and an appreciation of the distinctive intellectual merits of scientific ways of thinking.

59.2.2 An Ontology of Difference

Roth's (2008) work "Bricolage, metissage…" provides an example of CSSE work that goes beyond pedagogical practice, into the realm of ontology and linguistic meaning.

Roth begins with an analytic claim about language: that being different is generally understood as merely the negation of being the same. Roth argues that, when *difference* is treated as conceptually secondary, instances of identity are valued more highly than instances of difference. Whatever fails to conform to an accepted standard, Roth claims, is considered to be not merely different, but deficient, inferior.

Roth sets out to reverse the posited evaluative bias. He proposes that *difference* be conceived as the primary ontological category, as a concept that is "in and for itself" (p. 898). *Identity* would then be conceived as merely a limiting case of difference, an ideal state that is never fully achieved in actuality. Roth proposes that an ontology of difference should replace what he claims is the currently accepted ontology of purity.

Roth's empirical claim about the negative value currently accorded to difference is problematic. Contra Roth, it seems that whether sameness or difference is more highly valued depends on the type and context of the particular judgment of value. For example, in a dog show, sameness, i.e., close conformation to a breed standard, is the value sought; in a film festival, it is likely to be difference, originality, creativity, and novelty that are most highly valued.

The epistemological implications Roth sees in the proposed ontology of difference are problematic. Knowledge, Roth argues, on this view would no longer be conceived to be a single self-consistent ideal essence.[14] Instead, knowledge would be understood as a "singular plurality" that is constituted by myriad concrete instantiations of knowing. According to Roth, this means that knowledge must be

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[14] Knowledge is not in fact generally conceived today in this Platonic sense, particularly not in the context of modern science; see Sect. 59.3 for further discussion.

conceived as comprised of many different and mutually inconsistent knowledges. We must, on this view, relinquish "…the idea of *one* true scientific knowledge against which all other forms of knowledge are evaluated, asked to be abandoned, and, still worse, to be 'eradicated'…" (2008, p. 903).

Roth takes his ontology of difference to mean that any cultural accepted interpretation of a term such as "knowledge" counts as a legitimate expansion of the set of all referents of the term. This might, at first, seem to be a laudably open and accepting interpretation of knowledge. The problem is that terms that are given an infinitely extendable reference lose their value as communicative tools. Once there are no limits to the reference of a particular term, there is no longer any communicative point to be served by using the term.

Contra Roth, the crucial linguistic goal is to clarify the different usages of the terms "knowledge," "science," etc., to better understand the various interconnected, or inconsistent, meanings of the terms. Roth's approach, which is to expand the extension of the terms by broadening their definition indefinitely, is linguistically counterproductive.

The difficulties with Roth's ontology of difference, with its conceptual consequences, become apparent when Roth applies his ontology to the practices of science education.

59.2.3 Hybridized Knowledge

Roth develops an account of knowledge that he terms "hybridized knowledge." Roth observes that a global cultural diaspora is under way and that diasporic persons struggle to form new, composite identities that allow them to accommodate to a new culture while retaining cherished aspects of their original culture. Roth then argues that the culture of modern science is distinctive in being fundamentally foreign to *all* human beings and that all persons are diasporic with respect to science. Science, Roth observes, demands that familiar everyday concepts be set aside in favor of concepts of science that are, in a sense, nonnatural, i.e., intuitively implausible. In this, Roth is correct. For example, the familiar notion that the sun circles the earth, rising in the morning and setting in the evening, is dismissed by modern science, because it has been shown to be false. The familiar but discarded view, according to Roth, becomes "…an affront to the legally embodied and administratively enforced culturally (scientifically) correct one-and-only way of explaining this phenomenon" (2008, p. 894).

It is, however, contrary to the scientific norm of continuous organized skepticism for science to coercively enforce belief in the way Roth states. It is possible and common for demonstrably false but familiar ways of speaking, and thinking, about the world to persist alongside scientifically well-warranted theories, when serious consequences are unlikely to arise. But, there are circumstances when the consequences of such nonscientific belief are or would be serious. When certain social policy issues are decided, it is desirable that the most current scientific knowledge be employed. For example, it is common in some cultures to require that children be vaccinated against certain communicable diseases before beginning school. The relevant scientific knowledge is so well warranted that, in the interests of public welfare, even those who disbelieve in vaccination are nonetheless generally required to comply with the vaccination policy. It is possible that this sort of social employment of scientific knowledge counts as the legal and administrative imposition to which Roth objects. There are indeed issues of social ethics that arise with respect to the social use of scientific knowledge. At the most fundamental level of analysis, the reliance upon scientific knowledge in social policy decision-making can be justified only if there is something distinctively valuable about scientific knowledge, when compared to bodies of belief otherwise generated. Such a distinctive value of scientific inquiry and knowledge is what Roth is denying.

Learning modern science on Roth's view is inherently a matter of cultural suppression and the imposition and enforcement of the privileged culture of science. Every person studying modern science, Roth holds, resists that cultural suppression and struggles to construct a hybridized version of knowledge that incorporates the science into the familiar. Roth provides an example of the problems faced by the diasporic science student. He examines a doubly diasporic situation – English-speaking students who are learning science in French, in an immersion context. Roth finds that the students employ a hybrid lingua franca that incorporates elements of both French and English. The same hybridization process is seen in the students' understanding of science concepts.

Roth reports that, after 8 years of learning French and science, neither the language nor the science of the students is satisfactory to their French and science teachers. Roth, though, chides the teachers for evaluating students on the basis of the traditional ontology of sameness. These teachers, in his view, mistakenly believe that modern science and French have ideal essential forms that should be accurately replicated by the students.

Roth evaluates the students' work, instead, in light of his new ontology of difference. He interprets the students' errors (departures from authorized usage) as positive effects of the creativity and tenacity of those who are doubly diasporic. Engaged in two foreign tasks, the students employ all of their cognitive resources, new and old. Roth argues that, in order to learn the new cultures, students must actively engage in them, prior to having achieved an accurate understanding of them. In Roth's view it would be miseducative to insist from the start on accurate replication, as this would inhibit the students' exploration of the two new cultures.

Roth argues that science teachers too often fail to accept and value such hybridized knowledge. Instead, they impose rigid norms of discourse, doing symbolic violence to the students, by disallowing their familiar culturally accepted forms of speaking, thinking, and knowing. The problem seems to be an unwarranted epistemological domination. Roth takes it to be problematic that scientific discourse is "…constituted and considered as superior to any hybrid discourse" (2008, p. 913), while familiar beliefs that originate outside the science classroom are considered to be "…a lesser form of knowing than the one to be inculcated" (p. 913).

59.2.4 Indigenous Knowledge, Indigenous Science

The concept of indigenous knowledge, and of indigenous science as the source of that knowledge, has an important place in the CSSE literature.[15] Proponents of indigenous science make the claim that long-resident peoples have, over many thousands of years, developed sets of culturally specific beliefs about the world and its dynamics. Nonliterate cultures have bodies of belief that have been preserved in strong oral traditions, which are said to have been handed down unchanged through many generations.[16] These bodies of traditional belief are considered to have successfully guided the cultures in acting in the world over vast periods of time, and given this, they are claimed to merit the term "knowledge" and to count as indigenous science.

Ogawa, a proponent of the concepts of indigenous knowledge and indigenous science, redefines "science" in a way that permits traditional beliefs to count as science. Ogawa adopts Elkana's conception of science, who states: "By science, I mean a rational (i.e., purposeful, good, directed) explanation of the physical world surrounding man" (1971, p. 1437). With that broadly inclusive definition in hand, Ogawa is able to conclude that "…every culture has its own science…its 'indigenous science'" (1995, p. 585). Given the redefinition of science, this is merely to say that each culture has its own rational explanation of the world.

The requirement of rationality might be thought to place some limit on what could count as science. But Ogawa makes it clear that, in his usage, even rationality is to be reconceived as relative to the cultural accepted beliefs. Each culture, he argues, has its own worldview, i.e., its own set of traditional beliefs, and each worldview gives rise to its own version of rationality. Having risen from traditional beliefs, each culturally specific concept of rationality invariably affirms that the culturally specific beliefs are "rational" in a culturally specific sense. Thus, the fact that a set of propositions about the world has been widely believed, over a great many years, is taken to count as good reason for continued belief, i.e., continued acceptance of the propositions as true. This interpretation clearly harks back to the work of Barnes and Bloor.

Ogawa is opposed to a doctrine he calls scientism. He first conceives scientism as "…believing uncritically in science…" (1998, p. 106), that is, believing *in* science "…without understanding science" (p. 107). Ogawa's point here is a good one: to believe in science uncritically would be epistemically problematic and would promote a tendency to accept any thesis on faith, as a doctrine never to be questioned. The solution to this problem would seem to be provision of more and better education in modern science, so that an understanding of science could replace "belief in" science. Yet this is not Ogawa's solution.

Ogawa sets out a second, and more standard, conception of scientism. Scientism, Ogawa writes, is "an ideology that identifies valid knowledge only with science"

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[15] See also Deloria (1997) and Snively and Corsiglia (2001).

[16] Though, in the absence of recorded accounts, it is difficult to test and verify this claim.

(p. 106), and he rejects scientism in this sense.[17] Ogawa develops the educational implications of his anti-scientism and begins with what appears to be a paradoxical claim, the claim that multiculturalism is an inadequate response to cultural diversity. This is so, he argues, because multiculturalism is too often conceived to require mere mention of scientists of diverse ethnicities and cultures and of the contributions they have made to modern science. He considers this approach problematic, because it involves the deprecation of the nonscientific traditional belief systems of indigenous or other nonscience-based cultures.

Multiculturalism might be conceived as requiring a restructuring of science instruction intended to more effectively induct students from diverse cultures into the culture of modern science.[18] Ogawa takes this induction into modern science to be itself a problem, because in the induction process students belonging to non-Western cultures become alienated from their own cultural roots. Ogawa is objecting to modern science in the way Merton considered to be an attack from outside, which is expected when the organized skepticism of science threatens long cherished beliefs. It is troubling that this attack on science "from outside" is now advanced from within the field of science education. Contra Ogawa, to develop the means to critique, and discard, aspects of one's traditional culture is an inherently liberatory process, increasing each student's cognitive and moral agency.

Ogawa proposes to replace the multicultural approach to science education with what he terms a "multi-science" approach. In keeping with Barnes and Bloor's analysis, science is to be reconceived as relative to cultural norms and practices of thinking and knowing. Given this, science educators should "…view Western modern science as just one of many sciences, that is, science in the context of science education need not necessarily be Western modern science" (p. 584). "Scientism," in Ogawa's second sense, would thus cease to pose a cultural threat, since every cultural belief system would count equally as science, by definition. Accepting the legitimacy of indigenous science entails rejecting the notion that modern science is the only source, or the best source, of knowledge about the interactive dynamics of the world.

Ogawa considers it imperative that the indigenous sciences of students, as well as the students' unique personal sciences, be included in science curricula, along with "Western" modern science, "…as one of the main curriculum emphases" (p. 592). Learning "indigenous science" is a matter of studying the ancient traditional beliefs of whatever cultures are included, and incorporating those various beliefs into one's worldview. Content courses in science teacher education programs, Ogawa adds, would need to be revised to include study of a wide array of traditional belief systems of indigenous peoples.

Curiously, modern science, which Ogawa terms "Western" science, is not itself conceived to be an indigenous science. Ogawa observes that many in Western cultures feel no personal affinity to modern science and concludes that modern

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[17] Aikenhead (2001) provides another example of the anti-scientism position. See also Cobern and Loving (2008).

[18] See also Southerland (2000).

science is uniquely isolated from the everyday lifeworld of even "Western" people. Modern science, Ogawa holds, is inherently alienating because of its ontology: modern science "…pertains to a Cartesian materialistic world in which humans are seen in reductionistic and mechanistic terms" (p.589).[19] It is the alienation of modern science from any particular culture, Ogawa maintains, that allows individuals in diverse non-Western cultures to do modern science. That modern science is not grounded in a specific culture, but is open to all, is taken as evidence that it is merely "…a theoretically materialistic science, …a kind of game open to anybody who will obey its rules" (p.589). The openness of science to all participants might seem to be to its credit, dispelling worries that students from non-Western backgrounds are unsuited for the study of science. But Ogawa sees the openness of modern science as a defect. Science, having destroyed the students' indigenous culture, leaves them adrift, belonging to no culture. The exclusivity of indigenous cultures seems to be, for Ogawa, a positive thing.

Western modern science, in Ogawa's view, is a culturally oppressive institution wherever it occurs. The authority of science, he states, arises only from the consensus of its scientists, and he holds that this socially powerful group imposes its views on nonscientists, i.e., the cultural majority, without their understanding or consent. "[W]estern modern science is justified only by the scientific community itself. All other institutions have been excluded from the 'inquisition' of scientific justification and are expected to accept it without objections or doubts" (1995, p. 589). According to Ogawa, in every cultural setting, including that of the "West," both science teachers and students feel modern science to be a foreign imposition.

The autonomy of science, with its organized skepticism toward long-standing traditions of belief and practice, which Merton lauded, is generally taken in the CSSE literature to be a negative thing. Science education is a matter of indoctrinating students into a destructive worldview, imposed on students against their will. Roth, for example, writes:

> One of the key concerns I have with science education is that it is little different from what religious education has been in the past. It is a form of indoctrination into a form of thinking about the world that has been shown to be detrimental to the well-being of our planet that we both constitute and that is our home, our dwelling. (Barton et al. 2009, p. 194)

It is true that the growth of the body of scientific knowledge has permitted the development of effective technologies that have enabled an enormous increase in the size of the human population. There is little doubt that science has contributed in this way to the creation of serious environmental problems of global scope. But it is the use to which scientific knowledge is put, coupled with a lack of knowledge of or a willful blindness to the consequences of that use, which creates the problems, not the content of scientific knowledge per se. Knowledge of the dynamics of the world is needed if we are to ameliorate the environmental and social problems we face. The methods of scientific inquiry, developed in the context of continuous

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[19] If Ogawa is classifying Descartes as a materialist, his understanding of perhaps the most famous dualist among Western philosophers is deficient.

critical evaluation in an open community of inquirers, are means of attaining understanding of the actual dynamics of the interactions that constitute the world. The set of scientific methods is understood to be subject to expansion and revision. There is no bar to the incorporation of new methods, provided that the proposed new methods prove able to pass the tests of the organized skepticism essential to science. There is no sense in placing one's confidence in "other" ways of knowing, that is, in precisely those ways of fixing belief that have not been tested or that, having been tested, have failed.

59.3 Philosophical Considerations About Science

Conceptions of science are grounded in philosophical conceptions of the nature of reality, knowledge, and truth. Radically different interpretations of these basic philosophical concepts are clearly possible. Because radically different interpretations will lead to fundamentally different judgments about the value of practices in science education, consideration of these philosophical concepts has a practical importance.

The difficulty is that the philosophical concepts are interrelated and form an intricate network of meaning; they seem to defy separation and independent resolution. Nevertheless, an effort will be made here to examine them here in a more or less linear order.

59.3.1 Scientific Inquiry, Scientific Knowledge

Science developed as an improvement on the everyday efforts of individuals to understand the dynamics of the real situations in which they live and must act. The term "science" refers both (a) to a particular version of the human activity of inquiry and (b) to the intellectual product of that activity, a body of scientific knowledge. Popper's explication of scientific inquiry as a process of conjecture and refutation (Popper 1953, 1959, 1968, 1972) greatly clarifies the nature of science and informs this treatment.

Scientific inquiry, the activity, is the means developed by human beings to enable the discovery of the interactive dynamics of whatever exists, occurs, and interacts, i.e., the nature of reality. The aim of scientific inquiry is to develop explanatory theories about the world that are true of the world, that truly state the dynamic interactions that constitute the world. Scientific inquiry is an ongoing process of self-criticism, directed at the body of scientific knowledge and at the processes of scientific inquiry. The emphasis on continual self-criticism and improvement permits the hope that scientific knowledge, the product of scientific inquiry, will be increasingly determined by the interactive dynamic systems that constitute the world. There is, however, no guarantee that the process will lead to true statements about the world. Even if a statement or set of statements is in fact true of the dynamics in question, it is, by virtue of the nature of the scientific inquiry process, impossible to definitively, absolutely prove that it is true. Judgments about the truth of scientific statements are the all that can be had. Continual openness to the possibility of error is a necessary feature of scientific inquiry. Theoretical structures are always held open to improvement or replacement. Incompatible theories are taken to be in competition.

New judgments, based on new evidence, and/or on new analyses of existing evidence, are continually being made about the relative merit of competing theories. For this reason, the best-warranted scientific theories to date, are generally the more interesting and are the best bet when seeking to guide action. There are no guarantees of successful action, however; actions may fail even when guided by a true theory.

Scientific inquiry is a communal human activity. It requires a group of people acting cooperatively in pursuit of the same goal, the production of an objective body of knowledge of the world, and sharing a distinctive set of norms, methods, and institutions. Science requires a community and a community having a particular and distinctive culture that promotes the general aim, the search for truth. Maintenance of an open, sustained, cooperative, and critical discussion among qualified persons about the theories under evaluation is a necessary condition of scientific inquiry. The institutional structures of science are necessary for that maintenance.

Maintaining a self-critical attitude toward one's existing beliefs is made considerably easier by the public and interactive critical norms of science. The institutions of scientific inquiry, when they are working well, serve as guardians of the constraints of objectivity. Scheffler states that "[t]hese controls [on belief], embodied in and transmitted by the institutions of science, represent the fundamental rules of its game" (1967, p. 2). Ross et al. also consider the institutional arrangements of science to be the key factor in the demarcation of science. "…Science is, according to us, demarcated from non-science solely by institutional norms: requirements for rigorous peer review…requirements governing representational rigour with respect to both theoretical claims and accounts of observations and experiments…" (2007, p. 28). Despite human cognitive shortcomings, we can "achieve significant epistemological feats by collaborating and by creating strong institutional filters on errors" (p. 28).

Critical discussion is a necessary prelude to the experimental testing of competing theories. Focused on the logical merits of the theories, this discussion determines which theories should be experimentally tested and how those tests should be structured. Critical discussion is also required after the experimental testing, to assess the results of the testing. The rigor of communal critical discussion cannot be achieved by a single individual nor by a few individuals of like mind. Each human being is naturally subject to various biases introduced by personal history, personal desires, fears, enthusiasms, etc. The requirement that critical discussion be open and communal provides a corrective influence, as the various biases of the participants are counterbalanced. In any effort to critically evaluate one's own thinking, the cooperation of others, who think otherwise, is invaluable. But, the scope of the discussion is not limitless. Competence with respect to the history and current state of the relevant body of scientific knowledge is a practical necessity. Scientific inquiry does not require the consideration of the groundless assertions of ancient mythologies.

Scientific inquiry requires the use of well-warranted[20] methods and instruments of objective inquiry, and participation in the social institutions of science, that promote adherence to the norms of science. The history of scientific inquiry is a history of innovation and continued improvement, not only in scientific knowledge but also in the methods, instruments, and institutions of inquiry process itself.

Scientific inquiry, in Popper's conception, proceeds by a process of "conjecture and refutation." The generation of new ideas, conjectures, or, simply, guesses about the world is a creative human act, and this is the necessary first step in scientific inquiry. The source of a new conjecture is not in itself important; conjectures about the world might arise from prescientific myths, from inborn dispositional beliefs, or from dreams, etc. But not all conjectures are equally worth testing. The better conjectures will be bold, i.e., will have high informational content, and will make claims about the world that contradict current theories.

Scientific method cannot be accurately characterized as a simple, and yet universal, set of procedural steps. But, it is not the case that any activity, nor even any inquiry activity, counts as scientific. Over time, diverse inquiry practices that serve particularly well in severely testing theories about the world are identified, formalized, and adopted, tentatively, as methods of scientific inquiry. The methods of scientific inquiry form a vast and highly varied set, which is always subject to testing, revision, expansion, and improvement. Judgments about the quality of methods used in an inquiry are made continually and can only be made by scientific peers who have the requisite technical methodological knowledge.

A body of scientific knowledge is the intellectual product of scientific inquiry. Explanatory theories about the world, and the critical discussions of them, constitute the intelligible content of scientific knowledge. It is necessary for further scientific inquiry that the contents of the body of scientific knowledge be formulated linguistically and/or mathematically and that these formulations be set out in a physical form that permits open public scrutiny and evaluation. All of the contents of scientific knowledge remain open to continued public appraisal, and the best-warranted theory at one time may, on reappraisal, be demoted or may be judged to be false.

The contents of knowledge, belonging to Popper's *third world*, i.e., the world of the intelligible, are objective, i.e., real objects, real existents in their own right. Though the intelligible contents of the physical body of knowledge are the products of human activity, these intelligible objects are largely autonomous, in that they have, in their own right, properties and relations that are unaffected by human thoughts about them.

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[20] The term "well-warranted" refers here to those theories, practices, means, etc., that have been subjected to rigorous testing and critical evaluation and have been judged to have done well in standing up to the scientific scrutiny, following Dewey's (1929) usage.

The current body of well-warranted scientific knowledge must at the least be internally consistent, if it is to have any prospect of being true of the world. Discovery of inconsistencies in the current theories about the world presents a scientific problem, to be solved by further scientific inquiry. A distinction is needed between current scientific theories, the possible truth of which is still being investigated, and theories that have been refuted or that have failed to succeed in competing with other theories. The latter remain in the body of scientific knowledge but are consigned to the archives, available for further scrutiny, but not considered in the scientific community to be worth further scrutiny.

A question is often raised: Is the content of the current body of scientific knowledge dependent on culture or on the world? The alternatives seem to be mutually exclusive, so it is not surprising that conflict has arisen over this question. Gieryn describes the conflict as a science war and places the combatants into two camps. Those in the "science studies" camp consider scientific knowledge to be culturally relative, simply a body of collectively accepted beliefs. Those in the "science defenders" camp consider scientific knowledge to be universal, equally applicable across cultures, a body of statements about the world that, if not true, are at least near to the truth (1999, p. 344).

There is no doubt that scientific inquiry is a historical process and that the events in that history are contingent, not necessary. Given this, the contingent events of human social life, and cultural circumstances, can and do affect the historical course of development of scientific knowledge. Given this, it is possible that activities of bona fide scientific inquiry could, in different and *communicatively isolated* human cultures, be developing differently over time. But it is a mistake to conclude, as cultural studies of science theorists generally do, that scientific inquiry and the intellectual product thereof, scientific knowledge, is therefore dependent upon the specifics of cultural history.

It is possible that members of two mutually isolated cultures could each independently develop a genuine culture of scientific inquiry, having the norms, practices, and institutions necessary for the practice of science and that these cultures would engage independently in scientific inquiry into the same natural phenomenon. It might happen that various explanatory theories are proposed in each isolated culture and that the competing theories are subjected to severe experimental testing and open and critical communal discussion in each culture. It is possible that judgments about the best theory of the entities and dynamics of the world in one culture would be substantially different from and inconsistent with the judgments of the other culture. The science developed in each culture is thus dependent, historically, on the unique course of events in each culture.

But the moment the isolated cultures come into communicative contact, the incompatible scientific theories come into competition. Assuming that it is the same phenomenon that is being investigated, there can be only one set of statements that truly states the dynamic interactions that constitute the interactive system in question. The presence of two or more different theories, each intended to be that set of true statements, simply sets out a new scientific problem. The situation would indicate to scientists in each previously isolated scientific community the need for further scientific inquiry to assess the relative merits of the competing theories. The theories are historically dependent on culture, but the truth, or nearness to truth, of the competing theories is not relative to culture.

The competing theories may persist side by side for a long time, pending evidence that refutes one or another of the theories. Perhaps each theory will give way to a new theory, one that is a better warranted and offers a better explanation of the phenomenon. But, in science, the appearance of two competing theories about the same phenomenon always presents a scientific problem to be solved. Refusal to engage in that reassessment of theories required by the norms of science is a clear indication that the supposed science of one of the cultures is not, after all, genuinely scientific.

It is rational to prefer, as a basis of action, the theory that has best survived severe empirical tests and communal critical discussion (Popper 1972/1995, p. 22). But acceptance of a scientific theory always remains tentative, no matter how successfully it survives severe empirical testing and critical evaluation.

59.3.1.1 Falsifiability

It is impossible to speak sensibly about science unless science can be conceptually distinguished from nonscience, from pseudoscience, and from speculative metaphysics masquerading as science. Popper distinguishes scientific theories from other theories that "…though posing as science, had in fact more in common with primitive myths than with science" (1953/1988, p. 20). It is clear from the CSSE literature that the demarcation problem is still a live question and one that has practical consequences both in education and in society at large.

Popper argues that the key to the demarcation problem is the falsifiability of scientific theories. To be scientific, a theory must be "…*incompatible with certain possible results of observation*" (p. 22, emphasis in original). According to Popper, "[a] theory which is not refutable by any conceivable event is non-scientific. Irrefutability is not a virtue of theory (as people often think) but a vice" (p. 22).

The initial conjectures about the world, which will be influenced by the contingencies of observation and inductive inference, must be formulated as testable hypotheses that specify what events must occur, when specified actions are taken under specified conditions – those actions under those conditions constitute the experimental test. Observing the events expected to occur provides a measure of confirmation of the theory; repeated confirmations are the basis of inductive inference that the theory is likely to be true or near true.

Inductive reasoning fails, however, as a method of scientific reasoning, because the scope of every scientific theory must go beyond the evidence obtained from any finite set of confirming instances (Popper 1953, 1959, 1972). In contrast, observation of events predicted by theory to be *impossible* serves logically to show the theory to be refuted. If the observation is judged in the scientific community to be a good one, if it is replicable, and judged not to be the result of error, the rejection or revision of the refuted theory is logically required.

Popper's falsifiability criterion for science does not constitute a decision algorithm to be mechanically applied to particular theories. It is not the case, in theory or in practice, that a single failed prediction is sufficient to falsify a theory. It is unlikely that events observed will perfectly match the events predicted based on a hypothesis intended. The events in the world that constitute the context of the experiment will affect the observation process in unanticipated ways. Calculations from the theory of the observations that would falsify the theory will include assumptions that are not well grounded and be incorrect. Judgments about the meaning of particular experimental results are an ineluctable part of the process of scientific inquiry.

59.3.1.2 Science and Pseudoscience

The ability to distinguish science from nonscience and from pseudoscience, and good scientific inquiries and theories from poor, is of the utmost cultural importance. Goldacre gives a detailed account of the prominence of pseudoscience in contemporary medical practice, in the form of complementary and alternative medicine [CAM]. Goldacre identifies a number of factors that work to undermine public understanding of science, even in cultures that one might expect to be most thoroughly scientific, and draws a discouraging conclusion. Addressing purveyors of pseudoscience, and opponents of genuine science, Goldacre says, "You win":

> …you collectively have almost full-spectrum dominance. Your ideas—bogus though they may be—have immense superficial plausibility, they can be expressed rapidly, they are endlessly repeated, and they are believed by enough people for you to make very comfortable livings and to have enormous cultural influence. You win. (Goldacre 2010, pp. 253 and 254)

Goldacre, however, sets out to counter the trend and explains crucial aspects of scientific reasoning that differentiate science from pseudoscience. Bausell, also focusing on the plausibility to many of complementary and alternate medicine, identifies numerous impediments to reasoning which plague human beings: "the family of logical, psychological, and physiological impediments to connecting cause and effect that necessitates the conduct of scientific research in the first place" (2007, p. 35).

Oreskes and Conway, in *Merchants of Doubt* (2010), document current efforts in the United States to keep well-established scientific knowledge from affecting governmental policy decisions. One effective tactic is to call for *more* science, for sound science, for critical reassessment of scientific findings. Such calls might seem to be the epitome of dedication to the methods of science. The problem is that well-warranted scientific knowledge is often countered and effectively undermined by well-funded disinformation campaigns that promote pseudoscience as science and that denounce genuine science as "junk science."

The proliferation of pseudoscience is a major problem in contemporary society.[21] CSSE theorists contribute to the problem in consistently fail to distinguish science,

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[21] Also see Binns (2011), Gauchet (2012), Kitcher (1998), Morrison (2011), Wagner and Steinzor (2006), and Zimmerman (1995).

not only from pseudoscience but even from nonscience; even the possibility of drawing, the conceptual distinction is denied. This is the direct logical consequence of the CSSE conception that all collective systems of belief count equally as knowledge and that all methods of achieving collective belief count as but different sorts of science. In collapsing the distinction between scientific inquiry and other sorts of inquiry, CSSE theorists undercut educational efforts to bring students to understand the nature of science.

59.3.1.3 Objectivity

Objectivity is an epistemic virtue characteristic of science. Individual or collective objectivity is achieved to the degree that believing is influenced by objective factors, i.e., the controlling force of the dynamics of the world, and the constraints of logical consistency. Scheffler states the relation of science and objectivity:

> …*de facto* science articulates, in a self-conscious and methodologically explicit manner, the demands of objectivity over a staggering range of issues of natural fact, subjecting these issues continuously to the joint tests of theoretical coherence and observational fidelity. (Scheffler 1967, p. 13)

Daston and Galison (2010) trace the rise of objectivity as an epistemic virtue associated with scientific inquiry to the 1800s. Images of natural objects captured by mechanical devices, e.g., photographic plates, were considered to be objective because they would “preserve the phenomena” from the imaginative subjective impressions, intuitions, and biases of the inquirer. They conceive objectivity in this way: “To be objective is to aspire to knowledge that bears no trace of the knower – knowledge unmarked by prejudice or skill, fantasy or judgment, wishing or striving” (p. 17). Prior to the adoption of the ideal of objectivity, they claim, it was common practice for observers to discard discordant observations as defective and, guided by personal intuitions of truth and essential form, to seek out the examples that would seem to verify the favored theory.

To achieve an ideal state of perfect objectivity is in practice impossible and is sometimes conceived as an unnatural cognitive state for human beings.[22] But the employment of instruments that preserve the phenomena, coupled with public participation in studying the preserved artifacts, promoted the emergence of objectivity as an ideal or regulative idea for scientific inquiry. Objectivity, as an epistemic virtue, requires commitment to acquiring beliefs about the world that conform, as much as possible, to the actual states and dynamics of the world. In scientific inquiry, the goal is to design interactions, observations, that serve as tests of hypotheses about the world. Scientific institutions and norms are consciously designed to promote the achievement of objectivity.[23]

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[22] See Wolpert (1992) and Cromer (1993).

[23] See Longino (1990), for another view.

Wolpert argues that scientific modes of thinking about the world are radically different from commonsense thinking about and conceptions of the world. Commonsense ideas of motion, for example, are generally not correct, and the explanations of motion found in modern physics are strongly counterintuitive. "Generally…the way in which nature has been put together and the laws that govern its behavior bear no relation to everyday life" (1992, p. 6). The need to commit to objectivity as an ideal guiding belief formation is one factor that makes the scientific mode of thought so different from everyday casual patterns of thought. Objectivity requires a willingness to be critical of one's current beliefs, even those that are comfortable, traditional and/or cherished. "Being objective is crucial in science when it comes to judging whether [one's] subjective views are correct or not. One has to be prepared to change one's views in the face of evidence, objective information" (Wolpert 1992, p.18).

Cultural studies theorists of science education are on solid ground when they observe that many students experience considerable difficulty in the study of science. To achieve an understanding of scientific inquiry and scientific knowledge does require the elimination of erroneous beliefs. Some students may indeed refuse the option to learn scientific knowledge and methods of inquiry, opting instead to maintain nonscientific traditional beliefs about the world. But the value of the scientific inquiry as the means of gaining knowledge of the world remains.

Ross, Ladyman, and Spurrett speak out "in defense of scientism." They argue that scientific inquiry is in fact the only means by which well-warranted and hence likely-to-be-true beliefs about the world can be acquired:

> …science just *is* our set of institutional error filters for the job of discovering the objective character of the world—that and no more but also that *and no less*—science respects no domain restrictions and will admit no epistemological rivals. (Ladyman and Ross 2007, p. 28, emphasis in original)

The only way to make a plausible case for there being some *other* way of knowing the world is to reconceive "knowing" so that the term refers to something other than having an accurate understanding of the world. It would be better, communicatively, to choose a different term.

Knowing the world scientifically, while highly valuable, is by no means the *only* valuable state worth experiencing. Esthetically appreciating the world is an eminently valuable state and a significant part of the full human experience. Rejoicing in the world, valuing the world, feeling a passionate connection to and responsibility for the world, and having fun in the world – these are all valuable and worthy states to experience. Imaginative stories about natural events and their meanings can be profoundly moving, emotionally, and can convey important social and personal values and thus have value. But none of these states or activities count conceptually as knowing. To conceptually distinguish knowing states, and efforts to know, from other states and other efforts does not in itself diminish the value of the other-than-knowing aspects of life. The animus against scientism, and against science, seems to rest on an unrecognized assumption that only that which counts as knowing, or as the means to knowing, counts as valuable. Having accepted that assumption, it seems important to insist that all valuable aspects of life must count as "ways of knowing," albeit very different ways. The better resolution, though, is to reject the false assumption that the sole experience that is of value in life is knowing.

59.3.2 The Object of Scientific Inquiry

59.3.2.1 Reality

Questions about the nature of reality are questions of ontology. Some of these questions are of ancient origin, e.g., is reality made up of material substance, or mental substance, or both? Reality might be conceived dualistically, allowing for both physical reals and nonphysical mental of spiritual reals. Alternatively, reality might be conceived monistically, allowing for only physical reals, e.g., chairs, dogs, planets, stars, electrons, and photons, or, alternatively, for only nonphysical reals, e.g., spirit, mind, and consciousness.

Today the question might be whether the matter and energy of contemporary physics exhaust the realm of reality or whether there is something else, in addition to the physical, that is also real, such as the mental, the spiritual, the intelligible, and the divine, or perhaps, consciousness. To be other-than-physical, the posited reals would need to be unconstrained by physical dynamics.

Popper divides the real into three distinctive worlds. Popper's first world is that of the *physical*, including the dynamic interactions thereof; the second world is that of the *mental*, of subjective states of belief, of knowing; and the third world is that of the *intelligible*, of statements, arguments, theories, and scientific knowledge.

In Popper's view, science involves the real things of all three worlds. The first world, the physical world, is clearly involved: physical human actions that have observable physical effects constitute empirical tests of theories. The second world, the mental world, is involved: human believing, human thinking, is required in the generation of hypotheses and in the critical discussion leading to evaluative judgment.[24]

The third world, the intelligible world is involved: linguistic formulations of hypotheses, theories, and arguments are required throughout the inquiry process, and theories and the critical discussions of them constitute the body of scientific knowledge that is the product of scientific inquiry. It is the casting of thoughts into linguistic form, itself a physical form, that produces intelligible objects and makes possible the ongoing public, critical examination that is a necessary characteristic of science.

Scientific inquiry begins with theorizing about the interactive dynamics of the physical world. This is not to say that only physics can be scientific – systems of dynamic interaction can be studied at any level, and an ecosystem is as legitimate an object of scientific study as a system of subatomic particles. Dynamic states of

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[24] To call this the "mental" world accords well with common usage but can introduce unnecessary confusion, should the term "mental" suggest the traditional ontological dualism, with "mind" existing as a nonmaterial mental substance.

affairs of organic beings are as open to scientific inquiry as those of inorganic beings. Scientific inquiry into the dynamic states of conscious organic beings is equally feasible. Having a thought is not fundamentally different from having an urge or having a cold – all are complex dynamic states of affairs of organic beings. The mental world that Popper posits appears to be a part of the physical world.

To make sense of the practices of scientific inquiry, an assumption of metaphysical realism is necessary.[25] Metaphysical realism is the thesis that the world is objective, meaning that the dynamic interactions and resultant states of the world are as they are, regardless of any thought, wish, or belief about them.[26] There is a complication, though. Thoughts, wishes, beliefs, etc., are themselves objectively real; like all real thing/events, in a particular sense, these are mind independent. That is, the existence of a particular mental state is unaffected by thoughts, wishes, and beliefs about its being or having been in existence, except when there is an ordinary physical causal connection. This is not to deny that organismic states of affairs, including thoughts, beliefs, and desires, are, potentially, causally interactive with other objective real things and events. Causal interactivity is the very hallmark of the real, and if internal cognitive states were *not* causally interactive, that would be reason to doubt their physical reality (see Khlentzos 2004). It is to deny that the entities and interactions that constitute the world are dependent upon the operations of a postulated non-physical mind.

Scientific realism builds on the thesis of metaphysical realism. Scientific realism is the thesis that the theoretical entities in use in well-warranted scientific theories are to be understood as objectively real, and that statements about those entities are to be understood to be true, or false. Ellis sets out a well-developed version of scientific realist ontology. According to Ellis, the scientific realist accepts “that an ontology adequate for science must include theoretical entities of various kinds, and that it is reasonable to accept such an ontology as the foundation for a general theory of what there is” (2009, p. 23).

Ellis employs an argument to the best explanation in support of his scientific realism: “…if the world behaves *as if* entities of the kinds postulated by science exist, then the best explanation of this fact is that they really do exist” (2009, p. 24). He distinguishes descriptive theories, those that posit real entities, from theories that explain by developing idealized models of interactions. The idealizations employed in the latter, e.g., a frictionless surface, are not intended to be understood as really existing. The scientific realist has no need to take idealizations to actually exist.

In contrast, Ellis argues, the entities postulated by an accepted “causal process theory” should always be understood realistically. If theory A “is agreed to be the best causal account that can be given of the occurrence of some event E, and A is a satisfactory theory, then the entities postulated in A as the *causes* of E must also be thought to exist” (p. 31). The argument for real existence of theoretical entities is strengthened when the posited entities are found to have additional causal effects,

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[25] Although it could be that metaphysical realism is false and that the practices of scientific inquiry actually do not make sense.

[26] See Devitt (1984/1991), Leplin (1984), and Melnyk (2003).

beyond those initially predicted. Ellis, like Khlenzos, holds that "causal connectivity is what characterized real things…real things should have a range of different properties, and so be capable of participating in various causal processes" (p. 32).

Ellis observes that the metaphysics of scientific realism quite naturally accords with scientific practices of inquiry, for the simple reason that this metaphysics "has been developed out of science, specifically to accommodate the developments that have occurred in this area" (p. 115). Given this, it is unsurprising that scientific realism "makes good sense of the nature and structure of scientific knowledge" (p. 115). But this ontology, like any ontology, is not intended only to be used in the context that gave rise to it. Ellis argues that scientific realism is likely to provide a sound basis for understanding in other areas, such as mathematics, and moral and political philosophy.

The scientific realist position sketched out here is a controversial one. Many philosophers of science, and scientists, adopt instead an instrumental conception of science. Instrumentalism in this context is the thesis that the statements that constitute scientific theories are not to be understood as truth-functional claims about reality. Instead, theories are to be understood as convenient, useful mathematical devices that happen to work well when making predictions about observable events. Instrumentalists argue that it is *not* the task of physics to arrive at true statements about things that really exist, particularly when the posited entities are unobservable. Ellis's separation of descriptive theories from theories specifically intended not to be descriptive seems to accomplish the conceptual work necessary to end the dispute.

Real events in the world affect human well-being, for better or worse, and these events are notoriously unresponsive to organismic states of wishing, desiring, believing, etc. Human action in the interactive world is required; that action, to be sufficiently successful in meeting human needs, must be guided by beliefs that are true or near to true. Instinctive dispositions to act in certain ways under certain conditions must have been sufficient at some time in our evolutionary history. But such dispositions no longer suffice. Beliefs must be carefully chosen, formulated, and tested for efficacy in guiding action successfully. The best of the tested beliefs are considered to be known.

Scientific inquiry is often still motivated by the pragmatic need to know, though it is often motivated today by the simple desire to know. In either case, the general aim of scientific inquiry is to seek truth, and its more achievable goal is to produce explanatory theories that enable humans to understand the world and to act more or less successfully in the world. A genuine explanatory theory must make true or nearly true statements about real entities and their real causal interactions.

59.3.3 Knowledge and Knowing

The term "knowledge" is used in a great many ways.[27] It is often used to refer to a particular subset of beliefs, those beliefs that are coupled with a strong feeling of

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[27] See, for example, Sosa (2011).

certitude. Popper calls this the subjective sense of knowledge (1972/1995). Knowledge, in this subjective sense, is an organismic state of affairs of the individual; when the state of knowing is widely shared among a group of individuals, it is a cultural state of affairs. In either case, subjective knowing is an ordinary physical state of a very complex entity. Popper places these states of affairs in his second world, the world of mental entities, populated by knowings, as well as believings, desirings, wishings, fearings, etc.

A claim to *know* serves a linguistic function, that of providing a particular assurance. It conveys the speaker's claim that the proposition said to be known is not merely believed to be true, but is believed to be true for good and compelling reasons. When a person asserts that he *knows* that a storm is approaching, the intention is to assure the listener that this proposition is very well warranted, that it is true or near to truth, and that it ought to be relied upon as a guide to action.

States of individual or collective knowing can be divided into two sorts, based upon the quality of the inquiry process that led to the state of knowing. On one end of the continuum, there are casual inquiry processes, including minimal inquiries barely worthy of the name. On the other end, there are the carefully designed ongoing programs of concerted inquiry that count as scientific inquiry.

A casual inquiry process is often considered to be good enough to warrant the assertion "I *know*," particularly in everyday situations in which the stakes are thought to be low. Yet even at this low level of inquiry, there are standards. A body of casually acquired subjective knowledge is expected to be self-consistent. Revision and improvement of the body of knowledge is expected, by an ongoing assessment of the warrant of the beliefs, and the elimination of error. Confidently believed propositions which have been tested and have failed the test should lose the status of subjective knowledge.

Popper develops the concept of objective knowledge and distinguishes this from subjective knowing (1968/1995). Objective knowledge, in Popper's view, belongs to his third world, "…the world of intelligibles, or of *ideas in the objective sense*; it is the world of possible objects of thought: the world of theories in themselves, and their logical relations; of arguments in themselves; and of problem situations in themselves" (1978/1995, p. 154). These intelligible objects are man-made. But, having been made, these objects have an existence that is largely autonomous of the world of subjective thinking, believing, and knowing. The existence of objective knowledge does not require the existence of individual or collective subjective states of believing.

The objective body of scientific knowledge is distinctive in that it is the product of intentionally devised and tested methods of scientific inquiry. The goal of scientific inquiry is to generate theories about the complex dynamics that constitute the world that are true or near truth. The body of scientific propositions is gradually improved by the elimination of error, made possible by the process of severe testing and critical communal evaluation. The availability of this objective knowledge permits the gradual improvement of individual and collective subjective states of knowing.

There is a pragmatic advantage to employing the set of propositions that have best survived the scientific inquiry process to guide one's action. One will be better able to predict the effects of interactions in the world and to effectively act in the world. The severe testing and critical comparative communal assessment of competing theoretical explanations are the means to achieve this advantage. The norms of scientific inquiry and the institutional structures that permit and promote adherence to those norms are uniquely suited to developing knowledge in this subjective sense.

59.3.4 Truth

An important concept, truth, has been left for last. What is meant by the term "true"? The ordinary language usage of the term "truth" is explained well by the correspondence theory of truth. On this theory, a proposition about the world is "true" if and only if the relevant state of the world actually *is* the way it is stated to be. A state of the world is the truth-maker for every true proposition. Every true statement corresponds, in this sense, to some state of the world; every false statement fails to so correspond.

The correspondence theory of truth requires, clearly, that there be a world, but makes no assumptions about, nor has implications for, specific theories about the world. Any ontological theory can be matched with the correspondence theory of truth. When truth is understood as correspondence, the truth of a proposition provides a good explanation for the success of action taken on the basis of belief in that proposition.[28] Truth, understood as correspondence of the statement to the actual state of affairs, is the ideal goal of scientific inquiry.

Popper conceives truth as correspondence to reality, i.e., to the facts, to what is. Popper's conception of science requires this concept of truth. In developing the demarcation criteria for empirical science, Popper writes:

> …I was very far from suggesting that we give up the search for truth: our critical discussions of theories are dominated by the idea of finding a true (and powerful) explanatory theory; and *we do justify our preferences by an appeal to the idea of truth*: truth plays the role of a regulative idea. *We test for truth*, by eliminating falsehood. (Popper 1972/1995, pp. 29, 30)

The correspondence interpretation of truth is commonly accepted among philosophers; Vision (2004) develops a strong defense of a correspondence. But this interpretation is often considered by cultural theorists and postmodern relativists to be fatally flawed. The theory fails, it is often said, because there is no way for the human organism to have *direct access* to the actual states of the world, and there is thus no way to make the required comparison between (a) statements *about* the world and (b) the world itself. Absent direct access, it seems that on the

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[28] But note that true belief is neither necessary nor sufficient for successful action.

correspondence theory of truth we could never determine, with certainty, the truth or falsity of any of our statements.

There are several problems with the criticism. The argument at best only shows that without direct access to the world, humans could not *find out* which statements are true and which false. But, it would be possible to could keep the correspondence theory of truth and accept that humans are doomed to ignorance of truth. But this is not necessary – it would be possible to accept the claim that humans do not direct access to the world, but do have sufficient access to the world to make critical judgments, based on good reasons, about the truth of our theories.[29] Or, one could accept the claim that causal interactivity of humans in the world provides the only form of direct access that is needed.

If one rejects the correspondence conception of truth, one might opt instead for an anaphoric theory of truth, conceiving truth as a pro-sentence forming operator.[30] Or, one might adopt a coherence theory of truth. On the coherence conception, each statement in a set of statements is considered to be true, provided only that the set as a whole is internally self-consistent. In a coherence theory of truth, the truth-maker for a statement is not the state of the world, but rather the internal coherence of the set of statements. The problem with this conception of truth is that, on this view, different and mutually inconsistent sets of statements would all be true, provided that each set is itself internally consistent.

Alternatively, one could choose to eliminate the concept of truth from knowledge entirely. Scientific theories could be understood to be, not true, or nearly true of the world, but instead "empirically adequate." In this case, the only claim made with respect to the theory is that it adequately accounts for the data at hand. An empirically adequate theory is often considered to be replaceable by any of an infinite set of different theories, each of which also accounts for the data. More radically, theories in science might be conceived to be nothing more than convenient fictions, contemporary mythologies developed communally by adherents to the culture of science, having no advantage over the different mythologies developed in other cultures. On this view the sole criterion for knowledge is *viability*, i.e., the mere survival of belief in the proposition. This interpretation of the relation of truth to knowledge is the one that is often in evidence in the CSSE literature.

59.4 Conclusion

Reality, knowledge, truth, and science – these interconnected concepts must form a coherent set, if any of them are to make sense. The concept of knowledge requires that there be some object of knowledge, a reality, to be known, and which can be known, at least in part, if knowledge is to be possible. Truth, understood as

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[29] See also Lynch (2005).

[30] See Grover et al. (1975), pp. 73–125.

correspondence of propositions to reality, is a regulative ideal for knowledge, an ideal goal to be increasingly approached. There being no "book of correct answers," judgments must be made, continually, as to the quality of the body of knowledge developed to date, with the intention to improve upon the body of knowledge. Given this process, it should be expected that the best knowledge of the day will not be as good, i.e., neither as extensive nor as close to truth, as the body of knowledge that will be developed. But changes in the body of knowledge constitute improvements in understanding; they are not mere fluctuations arising from whim or fashion.

Scientific inquiry differs markedly from other means of belief acquisition in its explicit commitment to maintaining a continued attitude of critical skepticism toward the propositions of the current body of knowledge. Ongoing public testing of that which is currently accepted as knowledge is *de rigueur*, a necessary condition of science. Open, critical discussion of all aspects of the process of inquiry and the results of the inquiry is also necessary. Judgments that arise from that discussion are held open to question, and progress is conceived as the ongoing elimination of error. Intentionally seeking for error in the current body of knowledge is the goal of the inquiry.

Being fully real interactants, human beings have no shortage of access to reality, though understanding the interactions we experience is no easy matter. Having a need for such understanding, for knowledge, and also a passion for knowledge, human beings have developed a complex social institutional structure, science, that promotes the effort to understand the interactive dynamics of the world, to know. The social institution of science does not work perfectly in promoting knowledge of the world – this should go without saying. But this constitutes a social policy problem to be addressed, not an indictment against the social institution of science *tout court*. To have an organized social system dedicated to the testing of propositions about the world and open to criticism and improvement is better than not to have such a system. To make use of the scientific knowledge that emerges to guide individual belief and collective social policy is a good thing, better than to make use of beliefs otherwise produced. These are value judgments, not certainties, but they appear to be well grounded. If so, one of the principal educational projects must be to convey to new generations the nature and value of the social institution of science.

Matters that should be of major concern for science educators arise in the CSSE literature, traceable to the philosophical positions underlying much of that literature.

The chief concern is that, in the CSSE literature, scientific inquiry is not clearly distinguished from other sorts of activities nor is it held to be distinguishable. In the absence of this conceptual distinction, no method of generating propositions and of fixing belief in them can be legitimately excluded from the science classroom. The phrase "other ways of knowing" is ordinarily conceived to refer to ways of generating individual or collective systems of belief (subjective knowing) that are *other* than scientific. As such, they can be easily seen to be out of order in the science classroom. So, for example, a close reading of some form of sacred scripture, even though it would lead to subjective states of knowing, would be justifiably excluded. Close study of time-honored oral traditions about the world would, by the same token, be properly excluded.

But in the CSSE literature, purported other ways of knowing are reconceived and are taken not to be other than science, after all. Instead, they are taken to be forms of science, albeit radically different forms (recall Roth's ontology of difference and the "singular plurality" he employs in dissolving conceptual distinctions). Given this, ancient traditional stories about the world, as well as religious, ideological, and political doctrines, must be counted as forms of science, in the new, all-inclusive sense.

Explicit advocacy of this revision in meaning is common in the CSSE literature and is entailed when the philosophical groundwork of the CSSE literature is accepted. The loss of the concept of science as a distinctive form of inquiry generating a distinctive body of knowledge would constitute an enormous cultural change. The resultant cultural endorsement of nonscientific, and hence poorly warranted, belief systems about the world would have negative consequences. There are, first, negative effects on the young persons who are effectively denied access to modern scientific knowledge. This is, too clearly, a problem already, as educational systems fail to provide excellent science education to many students. But to intentionally link an inferior education in genuine science to the ethnicity and/or cultural background of the students, on the grounds that, for them, the study of modern science is a form of cultural suppression, considerably increases the ethical problem.

Second, there are likely to be negative social consequences, should the CSSE reinterpretation/destruction of the concept of science become fully accepted and standard in science education. Disapprobation of science, of scientific methods of inquiry and the resultant scientific knowledge, is already common in many societies across the globe – public discourse in the United States provides many examples. This is of concern because, in a representative democracy, widespread public disdain for science is easily transmitted into public policy.

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Chapter 60
Science Education in the Historical Study of the Sciences

Kathryn M. Olesko

60.1 The Historiography of Science Education

Historical scholarship since the 1930s has demonstrated that science education is not merely a minor subfield of historical investigation somewhat akin to institutional history, but is in fact central to understanding the contours of scientific practice, the formation of scientific personae, and ability of the scientific community to reproduce and survive. The historiography of science education to date has highlighted the ways in which educational settings sustain clusters of values, mental habits, and material practices that make possible the epistemological and social dimensions of science, including the transmission and popularization of scientific knowledge; the conduct of teaching and research; the training of recruits; and the public's views on science, including its social, political, cultural, and economic functions and the image of the natural world it conveys.

What occurs *inside* educational settings has much to do with what is *outside* them. The values, habits, and practices of scientific practitioners acquired in training are sometimes drawn from culture at large, as they are when craft or technical practices are adapted to the study of nature. Conversely, the values and habits cultivated in science instruction are part of the socialization of the pupil, and thus, science education participates in the construction of the individual, society, the state, and civil society. In addition, norms of social interaction in educational – and by extension, professional or workplace – settings have been shown to be as important as knowledge transmission in the course of training scientists or educating pupils at all levels of instruction. Crossings between "outside" and "inside" or between science and society provide a way to understand the mutual integration of science and culture, including national goals. Studies of science education have thus

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demonstrated that the vitality of the sciences and their practices has as much to do with their internal robustness as with their linkages to broader historical contexts, including daily life.

The history of science has reached a point where science pedagogy now has a secure place in understanding the nature of science. Simply put, science cannot exist without institutional and intellectual forms of disseminating knowledge and educating students and practitioners. Yet the historical study of science pedagogy transcends concerns for disciplinary reproduction in the sciences. The histories of science education are now many, and major review articles on the topic have become more common.[1] Historical approaches to the topic, however, are bifurcated into historians of science who view science pedagogy largely (but not entirely) as a problem in disciplinary creation and reproduction and historians of education who view science pedagogy and science popularization more broadly as a means of transferring value from institutional science to the public at large for the purpose of securing social stability, economic well-being, cultural hegemony, or political power (Rudolph 2008).[2] School science, popular science, university science, laboratory science, industrial science, and government science are some of the most salient sites of the many types of science pedagogy that not only sustain the scientific enterprise but also present the public with value-laden options of how to live their lives.[3]

While current scholarship takes into account the wide variety of institutional spaces in which the transmission of scientific know-how, intellectual and manual, occurs, much remains to be done. This essay treats scholarship by historians of science who have studied science education at either institutions of higher learning or sites of professional scientific activity (e.g., postdoctoral training). To a large degree, these studies have focused on the training of practitioners, but they have also considered the broader social, cultural, economic, and political functions of science education in producing secondary school teachers, administrative bureaucrats, and engineers or in realizing the ideological goals of dominant elites, such as the German notion of *Bildung* or the American Cold War ideal of a national security state. After a brief historiographical review, this essay examines four principal loci of historical investigation: scientific textbooks; science pedagogy, or how science is taught and learned; pedagogical practices in the generational reproduction of scientists; and finally the political, social, and economic dimensions of science education.

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[1] For overviews of the literature, see Macleod and Moseley (1978), McCulloch (1998), Mody and Kaiser (2007), Olesko (2006), Rudolph (2008), and Simon (2008).

[2] Concerning the transfer of values to the public, Rudolph (2008, p. 65) perceptively argues that the exchange goes both ways and that the boundary between scientific values and nonscientific ones is a zone of conflict worthy of historical investigation. Rudolph's review of the literature on science education and the lay public is exemplary (2008, pp. 69–75).

[3] For representative variety of settings, see Daum (2002), Dennis (1994), Geiger (1998), Holmes (1989), Kohlstedt (2010), Leslie (1993), Nyhart (2002), Olesko (1988), Olesko (1989), Pauly (1991), Rudolph (2002), and Schubring (1989). Studies of science instruction in primary education, secondary education, and the public sphere deserve their own dedicated historiographical reviews along the lines of Rudolph (2008).

It concludes by reflecting on how the emerging area of scholarship known as the history of the senses can be incorporated into the history of science education.[4]

60.1.1 The Early Twentieth Century

Before the 1930s dry-as-dust histories of educational institutions, dating from the late nineteenth to early twentieth centuries, had valorized the training of scientists in the industrialized world without casting a critical eye on the pedagogical process itself. With largely descriptive surveys underpinned by tables and statistics, these studies helped to create founder myths and institutional shrines within specific disciplines that subsequently proved difficult to displace in the historiography of the sciences. These myths helped to entrench a logical positivist historiography by viewing education through the lens of the progress of research. That approach faded in the 1930s when sociologists of knowledge, struck by the contrast between the liberal, rational conception of the individual promised by the Enlightenment and the conformities pressed upon the masses by totalitarian states, began to unpack the relationship between reason, behavior and social norms, and identity formation (Elias 1939; Fleck 1935; Schutz 1932).

Among this generation of sociologists of knowledge, Ludwik Fleck had particularly perspicacious insights into the nature of science learning in the context of what he called the "genesis and development of a scientific fact" – the general idea that facts are not discovered, but are rather made in a process that involved intellectual decisions, institutional practices, and social judgments that are all learned in training. Science education in his view created the mental and social frameworks necessary for the cohesiveness of a scientific community and for the creation and acceptance of new ideas. Education also established links to the past via the "syllabus of formal education" (Fleck 1979, p. 20). Fleck thus embedded the educational processes of socialization and training in broader contexts, claiming that "In science, just as in art and life only that which is true to culture is true to nature" (Fleck 1979, p. 35). Most relevant to this essay, Fleck believed that "initiation into science was based on special methods of teaching" (Fleck 1979, p. 112). But his views on science went largely unnoticed until the translation of his work into English in 1979. By then whatever he could have offered the historical analysis of science education was eclipsed by the popularity of Thomas S. Kuhn's *Structure of Scientific Revolutions* (1962) which, Kuhn later revealed, may in any event have had its origins in Fleck's work. Kuhn, however, quickly forgot he had read Fleck and could later only surmise his indebtedness to him (Kuhn 1979, pp. vii–ix).

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[4] I thank Michael Matthews, editor of this volume and of *Science & Education*, for permission to reproduce and paraphrase parts of Olesko (2006) in this essay.

60.1.2 The Later Twentieth Century

In the aftermath of the Third Reich and the ideological realignment of postwar educational systems into the Cold War intellectual factories for defense, studies of the social system of science fell into two distinct phases, both of which shaped perceptions of the historical significance of science education. The first, from the end of World War II to roughly the beginning of the tumultuous social and political movements of the 1960s, was marked by an ideological capitulation to a system that placed great faith in science and technology as guarantors of the strength of the nation state, whatever its political orientation. Science education became one means among many for bolstering national security and tipping the global balance of power, as had occurred in the United States, the Soviet Union, and Great Britain and other nations that became members of the nuclear club. It also became a sine qua non for developing states that aspired to become modern. Key concepts defining the social system of science originating in this period tended to follow politics and shielded science from a deeper examination of certain features of its internal operation, including the question of how science was learned in the first place. A prominent example is Polanyi's notion of "tacit knowledge" which rendered ineffable some of the techniques of science as well as the methods of how scientists were trained (Polanyi 1958).

60.1.2.1 The 1960s and 1970s

The 1960s marked the beginning of the second phase when methodological changes in the history of science lifted the veil of secrecy that had hitherto concealed aspects of scientific work, revealing more clearly the interweaving of scientific and social practices. From historians as diverse as Michel Foucault (1966, 1975), Thomas Kuhn (1962) and Jerome Ravetz (1971) came a matrix of fruitful questions about the role of science education in the practical work of science as well as in discipline formation and maintenance.

By viewing scientific education as a process of near totalitarian indoctrination, Kuhn highlighted the powerful role of science pedagogy in transmitting paradigmatic problems, solutions, skills, and other guidelines for scientific practice. Practical activities, including instruction and knowledge production, were united in what Kuhn called normal science, his epithet for everyday scientific practices and beliefs. In his view the external world intervened in scientific practice only during periods of crisis that evolved into paradigm shifts when methods and skills metamorphosed in response to cognitive dissonance (Kuhn 1962).

More sensitive to the nuances of science pedagogy than Kuhn, Ravetz prioritized the social dimensions of instruction over intellectual ones. Training in how to make the kinds of sound judgments that avoided the pitfalls of scientific research (i.e., unsolvable problems and the dead ends of fruitless research trajectories) attracted his attention more than the content of knowledge or the means of its transmission.

Yet Ravetz was also deeply indebted to Polanyi and could not abandon the notion that skills were tacitly learned under the guidance of a master scientific instructor much in the same way that craftsmen learned trade skills. By definition skill learning could not be the object of historical investigation because it was ineffable. Ravetz viewed teaching as an intensely personal process, one so personal that were the precepts of scientific practice made explicit, learning the craft work of science would be irreparably damaged. Despite his insights, his impact on the historical study of science education has remained limited (Ravetz 1971).

Historians of science education may still genuflect to Kuhn, but it was Foucault who most invigorated theoretical discussions of history of science education. His intentionally ambiguous use of the word "discipline" – as conceptual organization but also corporeal training *and* character development – united the social, moral, and intellectual normalizing functions of education (Foucault 1975). Foucault was persistently critical of historians of science for their inability to grasp what was at stake in the construction of scientific regimes. For him the notion of "discipline" encompassed a plethora of minor procedures with major repercussions. Enforced by institutions of higher learning and the legal apparatus, disciplining *made* the modern individual and hence was constitutive of the formation of both modern society and the modern state. In three particular components of disciplining, Foucault discovered, too, the social processes at work in the pedagogic formation of modern scientific disciplines: hierarchical observation, normalizing judgment, and the examination or test (Foucault 1975). Although Foucault's views were not uniformly adopted, historians of science echoed his point of view in their study of systems of examination (Clark 2006, pp. 93–140; Macleod 1982) and in their affirmation of the centrality of teaching to launching and sustaining the disciplines (Pyenson 1978, p. 94). In other respects, however, the views of Kuhn and Foucault were often at odds with what more empirically based studies have demonstrated (Simon 2008, p. 105).

60.1.2.2 The 1980s and Beyond

A third conceptual phase, the focus of this essay, began in the last decades of the twentieth century. This phase was characterized by a deeper examination of the empirical record of science education in local, national, regional, and global contexts; a methodological pluralism that circumscribed the interpretive power of theoretical studies of science education (based nearly exclusively on Kuhn and Foucault) and expanded the role of historical contingencies in the shaping of science and its pedagogical practices; and a recognition that while science education was a subject in its own right, it was also an important site for understanding not only the larger structure and operation of the entire scientific enterprise but also more broadly in the construction of modernity. Consequently the historical study of science education became a window on the larger political, economic, and social environments of which science was a part. Due to the dominance of the military-industrial-university complex in the post-World War II period, the focus of historical studies of science education was largely, but not exclusively, upon the physical sciences.

Historiographical developments since the 1960s have refined the methodologies used to study the trio discipline, pedagogy, and practice. While not abandoning institutional contexts, new approaches have nonetheless gone beyond them. An important fruit of this effort has been the detailed historical examination of the training of neophyte scientific practitioners, which in turn has led to a recasting of how disciplinary history unfolds. Yet the historical significance of pedagogical experiences goes beyond the admittedly artificial confines of disciplinary history to include social, political, cultural, and economic history. These larger contexts have shown how widespread and necessary the framework of support and approbation was (and still is) for science education, dispelling the idea that science education is a self-driven enterprise.

60.2 Scientific Textbooks

The study of scientific textbooks was among the earliest genres in the history of science education. It still remains the most popular. Textbooks are enticing as historical objects of investigation because they present neatly packaged compilations and arrangements of scientific knowledge suited for instruction. They also confound historical investigation because they represent a selective history of their subjects. These contradictory traits led Kuhn (1962) to view them as little more than static moments or paradigms in the history of normal science and so as constraining in their effect upon students. Fleck (1935, 1979), however, created a dynamic conceptual framework that illuminated their role in discipline formation. He viewed textbooks as part of an intellectual continuum, occupying a position between journal and vademecum (handbook) science and popular science. As an intellectual hybrid, textbooks both initiated students to scientific ways of thinking and preserved some contact with ordinary knowledge.

Recent scholarship has cautioned against defining the textbook genre too narrowly, as an organized distillation of the results of research and in contradistinction to scientific popularization. The boundaries between different representations of knowledge now appear more fluid, and the distinction between genres less clear. At the most general level, textbooks are indispensable sources for capturing how thousands of students (and not merely future scientific practitioners) are exposed to science and what image of science they are likely to form. In the mid-1980s, sociologists of knowledge reinforced the association between textbooks and discipline formation by defining disciplines as “knowledge assembled to be taught” (Stichweh 1984, p. 7). Textbooks now are considered integral to understanding not only traditional topics of historical investigation, such as the development of ideas, epistemological choices and debates, the taxonomy of skill-based learning, and even the social dynamics of science such as priority disputes, but also the shifting relationship between science and society and the transnational nature of science (Simon 2011; Vicedo 2012, p. 83).

60.2.1 Textbooks and the History of the Disciplines

A defining feature of historical scholarship on scientific textbooks is its emphasis on discipline formation. Chemistry textbooks have attracted particularly sustained attention in this regard. Hannaway (1975) pioneered this branch of the historical study of science pedagogy in his study of Andreas Libavius's *Alchymia* of 1597. Regarded as the first chemistry textbook, *Alchymia* organized knowledge and united knowledge with practical skills; proffered plans for a "chemical house" or laboratory where hands-on learning would take place; and, in Hannaway's view, offered an alternative to the secretive nature of Paracelsus's alchemy by creating open chemical knowledge. By teasing out *Alchymia*'s long-standing usefulness and popularity across the century after its publication, Hannaway argued that *Alchymia* made vital contributions to intellectual dialogue on the nature of chemistry – quite the opposite of the deadening routine that Kuhn had identified with textbooks.

Historians have since qualified Hannaway's ambitious claims without dismantling its position as a turning point in the history of chemistry textbooks. *Alchymia* spread Paracelsian techniques by incorporating some of them into chemistry – thereby uniting the practical arts with science and academic forms of argument – and so to a limited degree became a textbook that was suited for both university instruction and the needs of the practical arts. According to Powers (2012), Herman Boerhaave (1668–1738) completed the transformation begun by Libavius. Boerhaave took a didactic form of chemistry based on some skills and operations, but lacking in concepts suited for examining the properties of chemical species, and combined it with elements of alchemy, chemically based medicine, and experimental natural philosophy – all of which he believed could fill in the conceptual gaps of a didactic chemistry. Furthermore, according to Powers, the instrumental practices of these latter three subjects (practices Libavius did not fully address) were crucial in shaping the practical side of chemical instruction. The result was Boerhaave's *Elementa Chemiae* which, in 40 editions between 1722 and 1791, set a pedagogical and research agenda for chemistry and defined chemistry as both an academic discipline and a practical art years before Antoine Lavoisier. Powers noted, however, that the assimilation of *techne* into teaching at the University of Leiden was not easily done, but once accomplished, chemical instruction assumed a dual nature as both theoretically and instrumentally based, with each side influencing the other. Thus, both Libavius and Boerhaave used science pedagogy as a platform for defining chemistry as a discipline.

Bensuade-Vincent in her review of textbooks from the chemical revolution (1990) argued that textbooks not only serve as snapshots of a discipline, but they are also essential for understanding the formation of schools, and so they function as tools of training, professionalization, and standardization (Bensuade-Vincent 1990). In this vein Hall (2005) has demonstrated that Lev Landau's and Evgenii Lifschitz's *Course of Theoretical Physics* played a decisive social role in the 1930s and later in shaping a Soviet research school in theoretical physics by framing problems and techniques for solving them that later carried over into research practice. In this way Soviet theoretical physicists could differentiate themselves from other schools, such as Arnold Sommerfeld's (whose German school was also created through a distinctive pedagogy and a defining textbook, *Atomic Structure and Spectral Lines,* which went through several editions during the crucial phase of quantum mechanics in the 1920s). Hence, although some textbooks defined transnational scientific communities, these Soviet and German cases indicate that the social and intellectual training of scientists could very well result in more localized sets of practices.[5]

In some quarters it has become commonplace to define and even to identify a discipline in terms of how it is taught or even represented in textbooks (Simon 2011). Certainly the creative role of textbooks in *helping* to create the disciplines cannot be denied. As textbooks are widely translated, reach transnational audiences, and become the foundation of national examinations in the sciences, the urge to associate them closely with discipline formation is compelling (Simon 2008, 2011). Especially when the creative processes at work in textbook construction, revision, and translation are considered, the ability of textbooks not only to *define* disciplines but also to *reshape* them is incontrovertible. Textbooks are remarkably fluid intellectual products (Bensuade-Vincent et al. 2003; García-Belmar et al. 2005).

Yet there are limitations to this perspective. Chief among is the danger of viewing the evolution of a textbook as teleological – as inevitably and directly reaching the terminus ad quem of a "discipline." That approach creates a deterministic pathway of analysis that could obscure the historical significance of a textbook that goes off the beaten path. Textbooks can be transnational, but they are also historically contingent in both creation and use. They can be universal, but they are also sites of conflict and competition. Arguments over which textbooks to use (or even to create) in science education are instances where there are competing views of reality, interpretation, and method coming to terms with one another. Such arguments could also be indicative of a struggle for scant resources (as when representatives of different approaches compete for the same clientele) or a struggle for prestige (as when scientists define their allegiances through the use of a particular textbook in teaching). These and other adaptations to or constraints of context limit the universal and transnational nature of textbooks. And context, in turn, modulates the degree to which a textbook does or does not contribute to discipline building.

The persistence of local scientific practices (especially industrial ones of relevance to the sciences, such as chemical technologies) that resist incorporation into textbooks, for instance, forestalls their broader recognition and acceptance and makes their adaptation elsewhere difficult if not impossible (Lundgren 2006). Other countertendencies to discipline building include the production of textbooks that challenge what later become dominant approaches (say alternatives to Newtonian physics in the eighteenth and early-nineteenth centuries, including Romantic nature philosophy) (Lind 1993, pp. 278–314). Examining only those textbooks which fed into the dominant tradition would be to represent falsely what historical reality was at the time. Most textbooks also fail to address some of the investigative techniques and skills of scientific practice which are incorporated, instead, into laboratory manuals (Olesko 2005). A textbook may be a partial map to a discipline, but it is not the discipline as a whole.

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[5] As also demonstrated by Kaiser (2005a), Olesko (1991), and Warwick (2003).

60.2.2 Textbooks and Their Historical Contexts

Textbooks can also be viewed as focal points for many of the historical contingencies that shape both scientific practice and the roles of science and the scientist in society and so carry historical significances that transcend that genre. Their physical dimensions, for instance, are not boundaries that mark the "inside" and "outside" of science but rather can be likened to porous filters that permit the intermixing of several different cultural elements and so have been studied as a part of culture writ large. Recent scholarship has exposed the connections between textbook culture and the constitution of the public sphere; teased out the relationship between textbook production and social structure; and, most importantly, provided strong evidence that the decisive century in textbook culture may not be the nineteenth, when textbook culture matured, but the eighteenth, when textbook culture was just beginning.

A particularly productive locus of scholarship on scientific textbooks has been the team of Bernadette Bensaude-Vincent, Antonio García-Belmar, and José Ramón Bertomeu-Sánchez.[6] Their collective results are the most comprehensive, thorough, and innovative studies to date of the textbook culture in any of the sciences. To their credit they have viewed textbooks as active agents of culture, but not necessarily as carriers or even creators of disciplinary knowledge as early works in the genre, such as Hannaway's (1975), argued. They view textbook writing as a negotiation between author, public, press, and state (García-Belmar and Bertomeu-Sánchez 2004). The richness of their collective findings is in large part of the result of their ability to assemble international teams of scholars whose combined linguistic abilities enable them to examine cultures less well known and to achieve results attainable only through careful comparative histories. Of special note is the team's decision to examine the scientific periphery, including such places as Portugal, Hungary, and the Greek-speaking areas of the Ottoman Empire. Just as earlier works on science pedagogy during the Cold War adapted to a culture of secrecy and national security, this team's work on textbooks shows the impact of ongoing European integration.

Although their collective approach is largely empirical, their findings nonetheless mesh with earlier theoretical writings on science pedagogy. Of relevance to their project is Fleck's depiction of the historical role of publishing in sustaining science pedagogy where published knowledge becomes a "part of the social forces which form concepts and create habits of thought" determining "what cannot be thought in any other way" (Fleck 1979, p. 37). His account of the viability of scientific knowledge necessitates a reading public that takes an active part in the public sphere where discussions concerning the relevance and interpretation of scientific knowledge occur. So when Antoine Lavoisier's chemistry entered Portugal by way of Vicente Coelho Seabra's *Elementos de Chimica* around 1790, the absence of a local chemical community and a weak public sphere, constrained by the inquisition

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[6] A partial list of their projects includes Bensuade-Vincent (2006), Bensuade-Vincent et al. (2002), Bensuade-Vincent et al. (2003), García-Belmar & Bertomeu-Sánchez (2004), García-Belmar et al. (2005), and Lundgren and Bensuade-Vincent (2000).

despite the expansion of print culture under Maria I (1777–1792), were reasons why Seabra's textbook was not adopted (Carniero et al. 2006).

Likewise in Russia the cumulative effect of the Church's monopoly on printing was to stunt the growth of a healthy public sphere where the free exchange of information could take place, thereby also restricting the growth of scientific communities (Gouzevitch 2006). In the Greek-speaking regions of the Ottoman Empire along the western end of the Mediterranean, the dominating presence of merchant elites meant that practical knowledge, conversions (weights and measures, coinage, and the like), and navigational issues were more important than Isaac Newton's *Principia*, so the former dominated textbooks in the physical sciences (Petrou 2006; Patiniotis 2006). Yet in each of these cases, the limited audience reached by textbooks did not diminish their roles in creating conditions conducive to the future growth of the public sphere: to wit, they promoted the standardization of language, vocabulary, scientific idiom, and alphabet that would eventually promote a larger reading public and audience for the sciences.

Publication patterns in scientific textbooks thus help in understanding the social structure and technical and scientific interests of the region over which they are found. The strong elite merchant class in the Ottoman Empire accounts for Greek translations of textbooks on practical geometry, geography, and commerce (all were useful for trade) and the relative paucity of textbooks on physics and chemistry, which carried little of significance for merchants. Conversely, as Patiniotis (2006) has observed, the absence of social support can doom a branch of knowledge. Textbook distribution reflects the balance of power among elites, as it did in the Ottoman Empire where the laws of the marketplace were more important than the laws of nature.

Characterized by discipline building, university history, the reform and extension of the secondary school, and the professionalization of the career of the scientist, the nineteenth century is often considered the defining moment in the modern social and institutional forms of science education. Recent studies of scientific textbooks demonstrate, however, that the eighteenth century may actually have more to offer us in terms of *why* (rather than *how*) these changes took place. As Patiniotis (2006) has pointed out, the word *textbook* was coined in the eighteenth century. The protracted shift from Aristotelian scholarship to more recent knowledge, as took place in Portugal under the *estrangeirados* during a period of enlightened educational reform, suggests that the intellectual dynamics of textbook organization in the eighteenth century may have been more problematic and difficult than they were in the nineteenth. Likewise the rapid intellectual shift in those areas under Napoleonic rule, such as northern Italy in 1796–1797 where the new French chemistry was established by law under public educational reform acts (Seligardi 2006), calls to mind the popular and social support required to make the shift permanent.

60.3 Science Pedagogy

Yet textbooks have their shortcomings as historical sources: they cannot reveal what went on the classroom, and they provide little information on how students learned and what their experiences meant to them. Since the late twentieth century, historians of science have turned to other types of documents in an attempt to understand the behind-the-scenes activity of teaching and learning in the sciences. Lecture notes, problem sets, student notebooks, examinations, laboratory exercises, instructional instrumentation, and multiple varieties of unpublished, duplicated materials have become privileged ways of reconstructing what went on in the seminar, lecture hall, and practicum. When supplemented by complementary materials, some published and some not (such as personal correspondence; diaries; autobiographies; laboratory notebooks or simply notebooks; and published versions of lectures, often straight from raw notes), the resulting historical scholarship reached even beyond a deeper understanding of science instruction to reveal how dependent all aspects of science as a human activity were upon educational processes. From primary education to the professional level of postdoctoral fellowships, apprenticeships, and the acculturation of mature researchers to new institutional settings, pedagogy played a part.

To confine science education to the transmission of knowledge or to the internal practices of the scientific community, then, is to mischaracterize the historical roles of science pedagogy. Science education has played a role in forming value systems; the scientific self (mentally, bodily, behaviorally, sensory, affectively, emotionally); social norms, including where in the social hierarchy different kinds of sciences fell; gender relations, both in- and outside the sciences; the power relations that determined the relative position of science and scientists vis-à-vis the state, society, and the economy; the cultural function of the sciences; and, finally, the role and perception of rationality in modernity. Science pedagogy thus has become the fulcrum which rests some of the most important dimensions of modernity. With what regard science education was held and why, as well as how much support that it garnered from the state and society, have become key historical questions in the study of both local manifestations and larger systems of science instruction.[7]

60.3.1 The Pedagogical Dimensions of Science Instruction

An early focus in the study of science pedagogy was the introductory science course offered in colleges and universities. Although it goes without saying that introductory courses had to be carefully framed to both attract and retain recruits in the sciences, only slowly did historians realize that their constitution demanded historical explanation. Geison (1978), Holmes (1989), and Olesko (1991) in their studies of, respectively, the physiologist Michael Forster at Cambridge, the chemist Justus Liebig at Giessen, and the physicist Franz Neumann at Königsberg are three early examples of how student needs shaped the tenor and texture of introductory courses. The pedagogical strategies of these scientists were instrumental not only in

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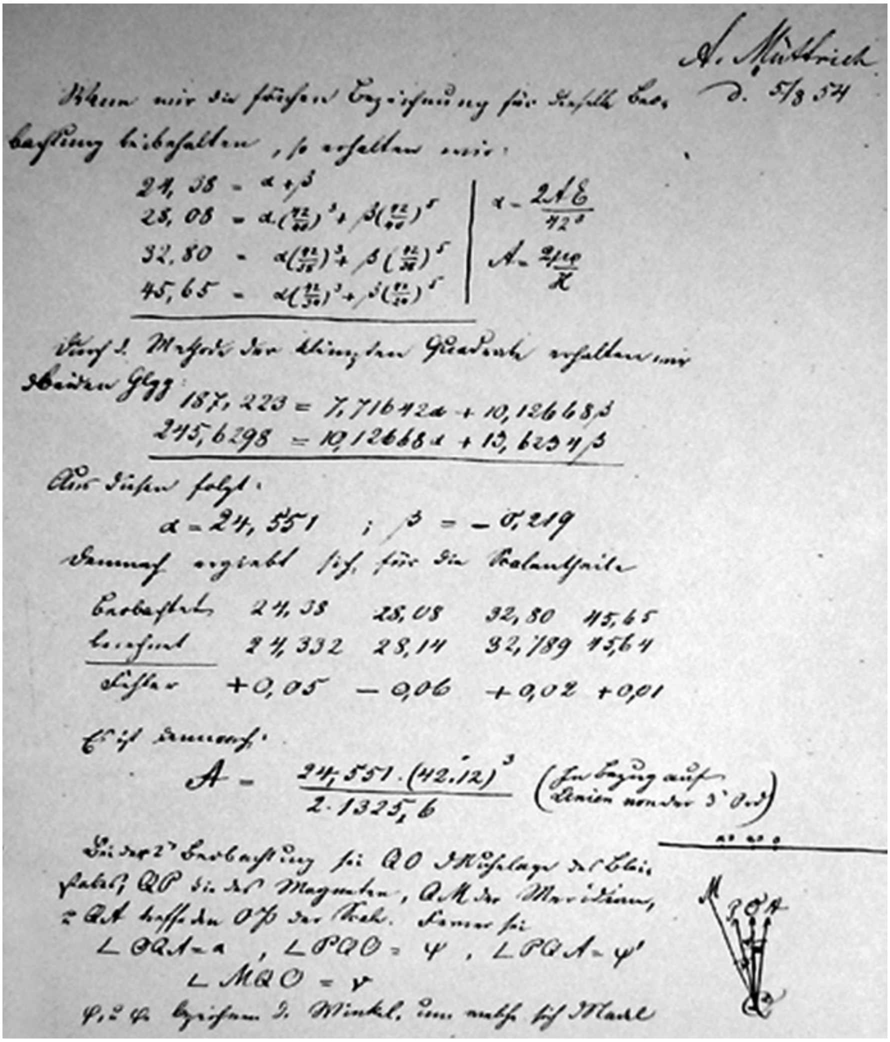
[7] Major studies that contributed to the broader significance of science pedagogy include Clark (2006), Gooday (1990, 2005), Gusterson (2005), Hentschel (2002), Josefowicz (2005), Kaiser (2005a, b), Olesko (1991, 2005), Pyenson (1983), Rossiter (1982, 1995, 2012), Schubring (1989), Traweek (1988, 2005), and Warwick (2003).

accommodating their student clientele but also in preparing them for advanced exercises and eventually research.

The instructional successes in each of these cases were dependent upon intimate knowledge of their students' prior preparation, a judicious integration of the techniques of research into teaching, and a willingness to deploy pedagogical techniques that both worked and accommodated student needs. Effective teaching also depended upon coordinating the introductory science course with secondary school science instruction. Foster's evolutionary approach to biology and physiology challenged the former anatomical bias in English physiology; Neumann's instrumental use of mechanics brought astronomical techniques into the core of physics teaching; and Neumann's and Liebig's emphasis on instrumental and error analysis promoted more rigorous standards of precision in physical and chemical investigations (Geison 1978; Holmes 1989; Olesko 1991).

Using the introductory science course as representative of science teaching and learning, though, is a bit like claiming that a textbook represents what is taught and learned. In both cases access to what actually went on in the classroom is limited. The sources available to Olesko in her study of Neumann's seminar, though, overcame that limitation. With seminar reports, seminar exercises, correspondence, lecture notes, and student problem sets, she was able to render how both teaching and learning transpired in the seminar. The results were unexpected. Rather than inculcating only the mathematical techniques of theoretical physics, Neumann concentrated instead on teaching his students the methods of an exact experimental physics: to wit, the determination of both the constant and accidental (random) errors of an experiment, the latter by the method of least squares. Bessel's exemplary seconds-pendulum investigation, undertaken for the determination of an official unit of length in Prussia, served as a model for the precision-measuring exercises of the seminar (Olesko 1991) (Fig. 60.1).

The cumulative effects of doing these exercises were transformative for students. Their investigations demonstrated how they acquired what Fleck called the professional habits needed to become a "trained person" (Fleck 1979, pp. 89–90). But something more happened. The emphasis on the precision and reliability of their data, the determination of constant and accidental errors, and the marginalization of techniques of approximation meant that there was an "epistemological and technical concern for certainty that at times bordered on obsession" (Olesko 1991, p. 17). That obsession, which Olesko called the "ethos of exactitude," failed to sensitize students to when the quest for epistemological certainty should end. The ethos became an ethic in the sense that it "guided professional actions and decisions by providing the ways and means of separating right from wrong, truth from error, and the even the called from the damned. It helped to define professional identities, structure investigative strategies, and identify significant problems" (Olesko 1991, p. 450). While this ethos thus played a determinative role in shaping the professional behavior of Königsberg seminar students, it also created psychological limitations that were often crippling: the quest for absolute precision was in the end an illusion, one that sometimes prevented them from seeing more pragmatic, and quicker, solutions to the problem at hand.



A. Müttrich
d. 5/8 54

Wenn wir die frühere Bezeichnung für dieselbe Beobachtung beibehalten, so erhalten wir:

$$\begin{aligned} 24,38 &= \alpha + \beta \\ 28,08 &= \alpha\left(\tfrac{42}{40}\right)^3 + \beta\left(\tfrac{42}{40}\right)^5 \\ 32,80 &= \alpha\left(\tfrac{42}{38}\right)^3 + \beta\left(\tfrac{42}{38}\right)^5 \\ 45,65 &= \alpha\left(\tfrac{42}{34}\right)^3 + \beta\left(\tfrac{42}{34}\right)^5 \end{aligned} \qquad \alpha = \frac{2AE}{42^3} \qquad A = \frac{2\mu}{K}$$

Nach d. Methode der kleinsten Quadrate erhalten wir die beiden Glgg

$$\begin{aligned} 187,223 &= 7,71642\alpha + 10,12668\beta \\ 245,6298 &= 10,12668\alpha + 13,6254\beta \end{aligned}$$

Aus diesen folgt:

$$\alpha = 24,551 \;;\; \beta = -0,219$$

Danach ergiebt sich für die Skalentheile

beobachtet	24,38	28,08	32,80	45,65
berechnet	24,332	28,14	32,789	45,64
Differenz	+0,05	−0,06	+0,02	+0,01

Es ist demnach:

$$A = \frac{24,551\cdot(42,12)^3}{2\cdot 1325,6}$$ (In Bezug auf Linien [illegible] 3° [illegible])

Bei der 2ten Beobachtung sei QO die Ruhelage der [illegible], QP die des Magneten, QM der Meridian, QA treffe den 0 Pkt der Skala. Ferner sei

$\angle OQA = \alpha$, $\angle PQO = \varphi$, $\angle PQA = \varphi'$

$\angle MQO = \nu$

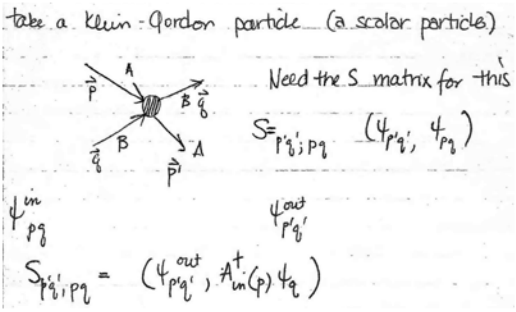
φ, φ' begreifen d. Winkel, um welche sich Nadel

Fig. 60.1 Gottlieb Anton Müttrich (1833–1904), notebook from the physical division of Franz Neumann's seminar at the University of Königsberg, 1854. In his determination of the horizontal component of the earth's magnetism, Müttrich applies the method of least squares, a hallmark technique of the seminar (Source: Arbeiten der physik. Abteilung des mathem. Physikalischen Seminars der Königl. Universität in Königsberg 1854–55. Heft 1 [21945/55]. Abt. Va Rep. 11 Planck 1836/26. Max Planck Gesellschaft Archiv, Berlin)

Like the Königsberg case, other detailed studies of science pedagogy have demonstrated how intensely local some practices were. Warwick's history of the Cambridge Mathematical Tripos, an examination on analytical mathematical methods rooted in Newtonian mechanics, rested on actual tests (but not on the students' answers, which would have revealed how students performed) and other sources that illuminated the process of learning, including the notes of the coaches who offered preparatory training for the test. He concluded that coaches developed such distinctive solutions to problems that when they were applied outside of the Tripos setting, the Cambridge connection was immediately recognized. These techniques were designed to enable the virtuoso performance necessary for scoring high enough on the examination to attain the coveted rank of Wrangler. But at the same time, they restricted analytical solutions to closed algebraic expressions and eliminated infinite series or approximate solutions. The ability to engage in research was not the goal of instruction, yet the impact of these techniques upon practice in physics was profound and long lasting. Of note, James Clerk Maxwell's *Treatise on Electricity and Magnetism* (1873) was not a response to the British Association for the Advancement of Science's study of a suitable electrical metrology (as had so often been assumed), but rather an attempt to resolve pedagogical issues left unsettled when the Tripos incorporated electromagnetic theory in 1868 (Warwick 2003).

The maintenance of the Cambridge coaching system relied on forms of sociability that not only mitigated some of the intense pressures of the examination but that also guaranteed the type of intellectual self-identification associated with a scientific school: face-to-face interaction, bonding with the coach, and small-group learning. This sociability was certainly similar to that attained at Königsberg, but the results were different. Analytical virtuosity was the goal at Cambridge; in Königsberg, competency to pass the state examination for secondary school teachers. At Cambridge the Tripos was for undergraduates, was not in service of a profession, and was part of an intensely local culture. At Königsberg, by contrast, the state examination was for graduate students, was designed to certify the suitability of students who wished to teach mathematics or science in secondary schools, and was administered by academics for the entire state.

Similar to the nineteenth-century examples of Cambridge and Königsberg was the twentieth-century implementation of the newly created Feynman diagrams as a quick way to train physicists, the largest group in the postwar glut of science students. Feynman diagrams were in this sense created to accommodate a particular student clientele. This example demonstrates how a technique that began as a *pedagogical* device ended up as a *standard* tool for solving particular kinds of problems in quantum electrodynamics. In other words, a pedagogical device became a practice not only in the field for which it was created but also in nuclear physics, particle physics, and various forms of experimental physics. Moreover, this new calculational and visual tool "transform[ed] the way physicists saw the world" and eased the conceptual difficulties in teaching quantum electrodynamics (Kaiser 2005c, p. 4). Although the population that used Feynman diagrams was composed mostly of graduate students, the physicists who found them useful constituted a community that recognized the diagram's ability to solve certain problems quickly. Feynman diagrams are thus an example of a pedagogical innovation that was created to accommodate a large student clientele but also became a means to ease the computational tasks in a growing field of science (Kaiser 2005a; Kaiser 2005c) (Fig. 60.2).



take a Klein-Gordon particle (a scalar particle)

Need the S matrix for this

$S_{p'q';pq} \quad (\psi_{p'q'}, \psi_{pq})$

ψ^{in}_{pq}

$\psi^{out}_{p'q'}$

$S_{p'q',pq} = (\psi^{out}_{p'q'}, A^{+}_{in}(p)\,\psi_{q})$

Fig. 60.2 Feynman diagram (Source: Kathryn M. Olesko, Notes for PHYS 490: Quantum Electrodynamics, Cornell University, Spring Semester 1973.Taught by Howard Tarko. Author's personal possession)

60.3.2 Science Pedagogy as Learning by Doing

While much of the historical literature on science pedagogy has focused on how science is *taught,* a small but growing body of scholarship has examined how science is *learned.* The methodological challenges of studying the latter are considerable, for the historian must find sources – notebooks, correspondence, and the like – that reveal the experiences, values, and attitudes of students as they make the transition from neophyte to practitioner. How brightly historians have been able to shed light on what transpired in exercises has depended upon available sources, not only written records of laboratory exercises but also instruments used for them. Success has been mixed, and much has to be inferred. Holmes' (1989) study of the relationship between teaching and research in Justus Liebig's Giessen chemistry laboratory relied on traces of laboratory teaching in either Liebig's publications or those of his students, and hence, his findings were necessarily incomplete. Liebig's concerted efforts to transform chemistry instruction through the introduction of the components of research procedures as smaller manageable exercises can only be inferred indirectly.

To varying degrees historians have been able to ascertain the exact exercises assigned to students and to assess their ability to complete them, but largely only for the case of physics. In the United States, Great Britain, and Germany, laboratory instruction began between the 1860s and 1880s, although, in Germany, smaller private instrument collections enabled hands-on learning decades earlier. But here too the results are skewed toward what documentary evidence is available. What is known about British laboratory practices also comes from comments in scientific publications. Far better reconstructed from printed sources are the reasons why such instruction succeeded in the first place and how that instruction was sustained. In Britain the factors contributing to the introduction of precise measuring methods into teaching laboratories between 1865 and 1885 were the development of precise measuring methods in the committees of the British Association for the Advancement of Science (e.g., for electrical standards), the inauguration of a student laboratory at Glasgow by William Thomson in 1855, and the example of professional physicists using precise measurements. Precision in measurement as a part of instruction was legitimated by the presence of a type of liberal education that emphasized rational and accurate reasoning, especially for future teachers; by the need to demarcate scientific methods from craft-based procedures; and by the association of precision measurement with economic production, especially in the telegraphic industry (Gooday 1990).

Industrial connections and lofty ideological goals were less in evidence in the United States when student laboratory instruction started after 1850. Here findings have relied on manuscript sources, laboratory manuals, and the printed record. Laboratory exercises became especially popular after the publication of Edward C. Pickering's *Elements of Physical Manipulation* (1873–1876), a manual adopted by most universities and colleges having the necessary space and instruments for such instruction (Kremer 2011). Laboratory instruction and instrument production were robust and flexible enough in America to accommodate student exercises in the new field of spectroscopy, which relied on precision gratings of sufficient resolution to give sufficiently differentiated visual results for instructional purposes and to do so at affordable cost (Hentschel 2002).

The development of laboratory instruction and the construction of university laboratories in Germany arose in response to student needs around 1870, although private collections afforded the opportunity to offer exercises earlier in the century, especially in Germany's numerous science seminars (Cahan 1985; Olesko 1991; Schubring 1989). For the German case, the archival record is rich and rewarding. Not only do historians have access to student notebooks, student exercises, lecture notes, and annual reports on teaching; they also have, in some cases, notebooks depicting the genesis of laboratory exercises. Such is the case for the most well-known and popular of laboratory manuals in physics, Friedrich Kohlrausch's *Leitfaden der praktischen Physik* (1870), which by 1996 went through 24 editions. Kohlrausch, who became an assistant to the physicist Wilhelm Weber at the University of Göttingen in 1866, worked for 4 years exploring which physical exercises worked best especially for beginning students. He left behind meticulous records of his experiences with exercises, as well as of student responses to them. Historical documents of this type, while rare, provide unsurpassed insight into how hands-on learning took shape, as well as student reactions to it (Olesko 2005) (Fig. 60.3).

60.4 Generational Reproduction

Generational reproduction is a complex issue in science pedagogy because it straddles traditional and nontraditional pedagogical settings. The reproduction of scientists is in one sense the direct result of the efficacy of science pedagogy. Yet that reproduction is also dependent upon robust pedagogical practices at the postgraduate institutions. At the simplest level, handbooks – compilations, distillations, and novel organization presentations of "what everyone knows" – are examples of higher-level pedagogies that sustain scientific practice in professional settings (Gordin 2005). At the next level, bureaucracies like standards institutions have to develop and deploy pedagogy simply to accomplish their mission. For instance, at Germany's Imperial

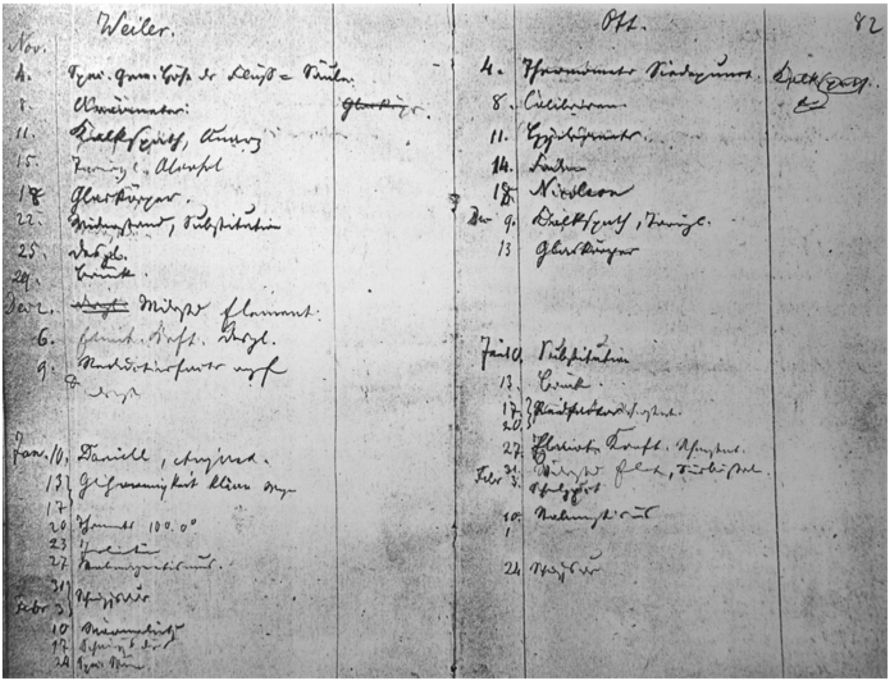


Fig. 60.3 Friedrich Kohlrausch's journal of laboratory exercises assigned to two students, November 1871–February 1872 (Source: Friedrich Kohlrausch Nachlass, Tagebuch Nr. 2504, Deutsches Museum Archiv, München)

Institute of Physics and Technology (established 1887), young physicists fresh from their doctorate had to acculturate themselves by learning the institutional norms of a bureaucracy whose purpose was both fundamental (as in standards determination) and novel (as in measuring black body radiation) (Cahan 1989). Indeed standards institutions around the world rely on higher forms of pedagogy not only for their own practitioners at home but also in order to normalize metrologies across the globe.

Such strategic interventions of science pedagogy have become apparent especially in instances of scientific disputes over the interpretation of data or when analytical representations fail to mesh. As Gooday has shown, pursuing solutions in the manner of the Mathematical Tripos could persist years after taking the examination, resulting in conflict with other professional norms. That's what happened to John Hopkinson who, in posing a solution to a particular electromagnetic problem using Cambridge techniques, clashed with a well-entrenched engineering graphical tradition. In the end Hopkinson accommodated the analytical and practical-graphical traditions, but his story is one that underscores the persistence of science pedagogy in making sense of the world (Gooday 2005, p. 142).

A special case of the strategic role of science pedagogy is found in the realm of nuclear weapons scientists. From 1945 to 1963 when the Limited Test Ban Treaty was approved and nuclear bomb testing went underground, nuclear weapons scientists enjoyed what Gusterson has called the "charismatic" era characterized by high levels of innovation and guidance from physicists whose experience with testing was indispensable for training new recruits in the ways and means of aboveground testing. In the 1970s and 1980s, however, routinization set in, with the result that innovation slowed, bureaucratic hardening occurred, and individual contributions to the effort were small. By the 1993 ban on all testing, experienced nuclear scientists retired; a new generation of scientists came on board to maintain devices they could not test in reality, and virtual computerized testing replaced real-life experiences with the bomb. Less and less knowledge and know-how about nuclear bombs were passed down generation to generation, resulting in an "involuted pedagogy of diminishing returns" (Gusterson 2005). In other words, the absence of real-life exercises (in bomb testing) means that the teachers (older nuclear scientists) could not train students (newer nuclear scientists) in how to use a test as a feedback mechanism to improve a nuclear weapon. In this case, generational reproduction did not so much as fail as wither away.

Yet perhaps there is no more important issue in the realm of generation reproduction than why women are so poorly represented among the practitioners of certain sciences, especially the so-called "hard" sciences. The gender implications and consequences of science pedagogy are critical problems of its history that beg for deeper analysis. As Rossiter (1982, 1995, 2012) has argued for the American case, women's gains in the scientific professions after initial marginalization and continued second-class status after World War II were ones that took place in the safe haven of women's colleges, through activism and organization, by piggybacking on the women's movement, and eventually favorable federal legislation. At the same time, however, educational benefits like the G.I. Bill of 1944 (and later amendments), the National Defense Education Act of 1958, the National Defense Student Loan program, and other Cold War measures to improve American standing in the sciences resulted in the further masculinization of science education at coed institutions.

In both science education and professional settings where postdoctoral training and professional grooming took place, institutionalized science pedagogy did more injustice than good for women scientists through its perpetuation and legitimation of sexism and other discriminatory practices. In addition systems of scientific training produced a gendered hierarchy of fields where the most impervious to allowing women entry were the hard core sciences. Traweek (1988) has demonstrated how training in high-energy particle physics promulgated gendered norms that worked against the incorporation of women. Over the long term, then, science pedagogy replicated the classical gender hierarchy of modernity.

60.5 The Historical Contexts of Science Education

As a disciplinary practice that often finds itself nestled closely to other branches of science and technology studies, the history of science often neglects, ironically, larger historical contexts as a venue for understanding the past. The result for the history of science education is a tendency to view key elements as static categories: discipline, pedagogy, practice, persona, textbook, and other units of analysis tend to acquire universal dimensions faster than they are understood as categories shaped by historical contingencies that change them over time. As a category of *historical* analysis, science pedagogy thus must be viewed from frameworks larger than either disciplinary or institutional history. The problem is to determine how large that framework should be and what factors are important within it.

For instance, the long-term transition from Aristotelianism to natural philosophy can only be understood by looking at what transpired in educational institutions, but to fully understand that transition, other factors such as the intellectual predilections and activities of religious orders have to be taken into account. Key agents in bringing about that transition were the Jesuits who, through teaching and textbook writing, were instrumental in institutionalizing newer frameworks for learning such as Cartesianism, Newtonianism, and, by the eighteenth century, hands-on learning (Brockliss 2006; Feingold 2003). At a later time, Boerhaave's *Elementa Chemiae* took shape within and absorbed the values of the local context of Leiden's religious, medical, and commercial cultures (Powers 2012). Great Britain's social transformation in the wake of industrialization played directly into Forster's innovations, which were implemented when Cambridge education became accessible to a broader socioeconomic clientele (Geison 1978).

In nineteenth-century Germany where mathematics had political value before it had economic currency, intimate forms of seminar instruction instilled in secondary school science teachers a belief in the powerful role of pure mathematics in interpreting physical reality, a perspective their students carried with them to the university (Pyenson 1977, 1979, 1983). Liebig and Neumann trained students for whom state qualifying examinations for secondary school teaching offered the possibility of upward social mobility and greater economic security (Holmes 1989; Olesko 1991).

Foucault thought that the problem of determining the relations of physics "with the political and economic structure of society" was to pose "an excessively complicated question" (Rabinow 1984, p. 51). Studies of physics pedagogy have nonetheless demonstrated a tightly woven connection between abstract knowledge and social norms and values. Warwick turned his study of the Cambridge Mathematical Tripos into a revealing window on Victorian culture by demonstrating how both mind and body were implicated in scientific and mathematical training. Coaching for the Tripos built character and cultivated the values of the Victorian gentleman. Public events surrounding the Tripos were filled with stress and sweat, ritual, and, for the highest-scoring Wranglers, an earned social status associated with merit (Warwick 2003).

Finally, a historically contextualized view of study of science pedagogy offers an unparalleled opportunity to examine the political dimensions, broadly conceived, of science education. Foucault is widely cited for his advocacy of viewing education as a political process: teachers, who controlled classroom disorder and reported on individual performance, were a strategic professional group whose members were the architects of power relations that both defined and disciplined the individual (Foucault 1975). But this focus on disciplining the subject has tended to ignore the degree to which individual agency was circumscribed by the systems and arrangements that make successful science education possible. Consider the nuclear scientists studied by Gusterson (1996). They learned while working in a nuclear weapons laboratory to create divided selves: a self that during the day created and maintained weapons of mass destruction and a self that on evenings and weekends cordoned off the workaday world in secrecy and silence. The history of science pedagogy is thus not only about understanding the transmission of knowledge and generational reproduction: it is more importantly about pedagogy as a moral and political practice where the examination of textbooks, pedagogical techniques, and institutions is part of understanding the structure of power (Giroux 2011), gender relations (Traweek 1988), civil society (Nyhart 2002), and other dimensions of extra-scientific contexts.

60.6 On the Horizon: The History of the Senses

Intellectual flexibility is a prime desideratum for the future of studies of science education: first, in order to make connections to new areas in historical scholarship and, second, in order to begin to analyze what is emerging as the next phase of science education in the early twenty-first century. Two developments – one historiographical and three contextual – loom large as challenges in writing the history of science pedagogy: the history of the senses, the emergence of massive open online courses (MOOCs), the corporatization of the university, and the growing number of technical professionals who bypass formal modes of science instruction en route to positions in the information technology and other economic sectors relying on scientific and technical knowledge. The controversies erupting over the latter three issues are fascinating (especially in the policy realm) and certainly worthy of study; but it is still too early to discern how they fit overall in the history of science education.

Nevertheless, these changes in the form and manner of science education at the beginning of the twenty-first century are designed to assist students where they need help most: in the mastery of foundational concepts. Scientists and policy makers argue that in the "learning science revolutions," training the eye is essential: "Visual representations are crucial to conceptualizing and communicating science, but students often have difficulty interpreting the models, simulations and graphs that are key to attaining a true understanding of science domains (Singer and Bonvillian 2013, p. 1359)." It seems appropriate then to conclude this essay with an examination of how the history of the senses can be incorporated into the history of science education as a tool of analysis as science instruction takes its next turn.

60.6.1 Integrating the History of the Senses

To a degree historians of science have taken the senses, especially vision, into account in their examination of science education. Most of these studies have focused on instruction in the life sciences, but the recognition that new printing techniques in the nineteenth century transformed textbooks has renewed the interest of historians of science in the role of vision more broadly in science instruction.[8] In addition to vision, hearing and touch are central to science learning, yet these have scarcely been studied and perhaps with good cause. Ideological frameworks, for one, make it difficult to isolate the historical roles of the senses. Karl Marx, among others, held that because the senses were alienated from the individual under capitalism, their history was impossible to write. Practical concerns too have impeded an examination of the senses in history. General historians have acknowledged over and over again the difficulties in writing the history of the senses even as they have maintained that cultural conditioning, which varies over time and across space, determines how individuals and groups deploy their senses (Jay 2011).

Science education is not only one of the strongest contributors to that cultural conditioning: science also cannot exist without sensory training, which in turn is a foundation for scientific judgment. Sharpening the senses to the point of achieving a disciplined focus (of several types) is a process that takes place both in science education and the practice of science. How science instruction enabled students to achieve focus is only beginning to be understood. Boerhaave, for instance, considered it essential to train students in the management of sensory data and for that purpose drew upon more general medieval pedagogical methods that fostered concentrated logical thinking. The new public course on instruments that he introduced in 1718 deliberately linked empirical information (the student's sensory perceptions) to chemical theory, trained students to interpret phenomena according to the instruments that measured their qualities (as in using Fahrenheit's thermometer to measure warmth), and educated the senses by disciplining them. His course on instruments thus complemented his course on chemical theory where the objective was to train reasoning processes (Powers 2012). Yet even as science education transformed the senses, the senses have a history of their own outside scientific contexts.

A transition from aural culture to an ocular one occurred in the passage from the eighteenth to the nineteenth centuries, opening the way for what both contemporaries and historians have called *Anschauungsunterricht* – a type of instruction that enables students both to visualize things and to interpret visual images. This passage entailed the cultivation of more impersonal forms of perception when abstract forms of representation replaced mimetic ones as the "culture of the diagram" replaced copying nature (Bender and Marrinan 2010). Moreover, visual learning expanded in the nineteenth century with the introduction of photographs, charts, spectroscopy, graphs, and X-rays. These instrument-mediated images revealed patterns, as in spectroscopy, that were typical of some aspect of nature (the wavelength patterns of elements) but also mysterious as to what they signified beyond a characteristic pattern. Spectral patterns were difficult to interpret, and so the student's perceptual apparatus had to be formally trained (Hentschel 2002, pp. 368–385). In the twentieth century, image-based science exploded to include electron microscopy, moving

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[8] See Anderson and Dietrich (2012), Bucchi (1998), Dolan (1998), Hentschel (2002), and Lawrence (1993).

images, and digital imagery. Concomitantly, images transformed textbooks to the point where "visual literacy" became essential both for science learning and as preparation for scientific research (Anderson and Dietrich 2012, p. 2).

60.6.2 Fleck and the Senses in Science Education

How might historians of science education take into account the history of the senses? Fleck's work (1979) could with profit be used here. By isolating three elements of learning that reshape (and so educate) the prospective knower – experience, cognition, and sensation – Fleck offers a way to view science pedagogy as a process that transforms science students into something they are not. The first, experience, concerns the formation of scientific behaviors like the acquisition of skills through observation and experiment and the ability to think scientifically, both of which Fleck claims "cannot be regulated by formal logic" (Fleck 1979, p. 10). What is seen in the form of "words and ideas," he warns, is merely the "phonetic and mental equivalents of the experience coinciding with them." They are merely symbols (p. 27).

Fleck challenges us to view the past of science education differently by replacing our rapt concern for the transmission of knowledge with a fresh look at the behavioral and psychological transformations of the science learner. Experience, sensation, and cognition are all socialized by training, a process he describes as a transformation of the senses: the "slow and laborious revelation and awareness of what 'one actually sees' or *the gaining of experience*" (Fleck 1979, p. 89). Experience thus reshapes not only our minds but also our bodies. Sharpened vision – the ability to identify phenomena, for instance – is indicative of a state of "readiness for directed perception" (p. 92). In a similar fashion, he interprets cognition as a social activity ("the most socially conditioned activity of man"), making knowledge "the paramount social creation" (p. 42). Cognition can, in fact, only be understood according to Fleck as a deeply historical and contextual process that renders the mind nearly one with the beliefs of others around it. So associations between knowledge and value (say when sickness is linked to sin) can only be explained through the lens of cultural history.

Taken together, experience, sensation, and cognition form the core of the professional habits that a scientist exercises day in and day out. They are the foundation of a "collective psychology" (p. 89) transmitted through education which keeps a scientist within the cognitive framework of his or her community. The main characteristic of a thought style is that through it a trained scientist progresses nearly automatically from a vague perception to a stylized and visual one "with corresponding mental and objective assimilation of what has been so perceived" (p. 95).

What makes Fleck's analysis of scientific training useful for the historical study of science pedagogy is its ability to account not only for *learning* science but also for *becoming* a scientist, a process that entails both mental and sensory transformations. Although the strength of a thought collective depends on the existence of active science pedagogies that can carry the thought style from one generation to the next (Fleck 1979, p. 39), Fleck believed that education, although a constraint that both compelled the learner to see only in a certain way, was also pliable enough to allow for the recognition of experiences that resisted their automatic inclusion in a community thought collective. In this way the learner could also become the creative scientist. Indeed he argued that the inability to recognize resistances was the mark of the "inexperienced individual" who "merely learns but does not discern" (p. 95).

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Part XIII
Regional Studies

Chapter 61
Nature of Science in the Science Curriculum and in Teacher Education Programs in the United States

William F. McComas

61.1 Introduction

In the past 50 years, advocacy for and scholarship in nature of science (NOS)/ history and philosophy of science (HPS) in school science has grown from a few scattered references in the science education literature to a veritable flood of support for, interest in, and research in the field.

A single definition of NOS shared by the majority of science educators would be difficult to find, but many would agree that NOS is the area of study in which students learn how science functions, how knowledge is generated and tested, and how scientists do what scientists do. McComas and colleagues (1998, p. 4) suggest that:

> The nature of science is a fertile hybrid arena which blends aspects of various social studies of science including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors. The intersection of the various social studies of science is where the richest view of science is revealed for those who have but a single opportunity [such as the case in school settings] to take in the scenery.

Just as there is a lack of complete agreement on the definition of nature of science, the name itself has engendered some debate. Some scholars suggest that it would be best to call this domain nature of science studies, history and philosophy of science, ideas about science, nature of sciences, nature of scientific knowledge, and views on the nature of science, among others. Of course each of these labels has some advantage over the others and is usually preferred by one group or another, typically for philosophical reasons. However, given the extent of scholarship associated with the NOS label and references to it, that will be the term used throughout this chapter.

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61.2 The Context of Education in the United States: An Overview

To fully appreciate this report on NOS in the United States, one must recognize the unique way in which education is organized and governed in the nation. At the founding of the republic in the mid-1700s, the original 13 governing entities coalesced into a nation. This new nation had two axes of command and control; the federal (or national) government reserved some powers for itself (defense and diplomacy as examples), and other responsibilities (education, for instance) remained in control of the states. In the United States, education is frequently mentioned as the quintessential *states' rights* issue. In many ways the individual US states such as New York and California function like independent nations; this is particularly true with respect to education.

What has evolved in the United States is a blend of laws, policies, governing traditions, and educational systems that have much in common but leave the ultimate control for schooling to the state rather than federal government. This is a unique situation, with Germany and perhaps only a few other nations sharing such a decentralized system. Each state, therefore, has full responsibility for teacher licensure, achievement testing, the establishment and maintenance of an education bureaucracy, school funding, and the development of educational goals and standards.

The US federal government, generally through the Department of Education (equivalent to the Ministry of Education in other countries), provides some guidance and encourages specific policies by commissioning studies and rewarding states through monetary support (or the threat to withhold such support). The US Congress is also involved in education with its mandate to produce a periodic "report card" on the education situation across the nation through the National Assessment of Educational Progress (NAEP). While it may be useful to talk about education in the United States, overarching statements about the nation as a whole are difficult to make with any assurance; we must look widely and infer liberally.

However, as we will see, the first decades of the twenty-first century have seen a gradual loosening of the states' formally tight grip on education policy with new sets of goals for school science under development by broad groups with representatives from the science and education communities with funding from public and private entities. Soon, virtually all of the US states will adopt what is called *The Next Generation Science Standards (NGSS)*. This is a major change in the educational governance in the United States with vast implications for assessment, teacher preparation, curriculum development, and classroom practice.

61.3 NOS in the Schools of the United States: Some Historical Perspective

There is no single moment when NOS and related ideas entered the educational area, but more than 150 years ago, the Duke of Argyll in his Presidential Address to the British Association for the Advancement of Science stated that "What we want in the teaching of the young is not so much the mere results as the methods and, above all, the history of science" (in Matthews 1994, p. 11). This may be among the first suggestions that an element of what is now called *nature of science* should be part of the school science curriculum.

A century later this view crossed the Atlantic Ocean to the United States, where the Educational Policies Commission *Report on Education for All American Youth* raised the promise of the use of NOS (1944, p. 132) by stating:

> These scientists are thought of as living men [sic], facing difficult problems to which they do not know the answers, and confronting many obstacles rooted in ignorance and prejudice. In imagination, the students watch the scientists at work, and look particularly for the methods which they use in attacking their problems . . .

In 1946, James Bryan Conant, educator, scientist, and president of Harvard University, delivered his famous Terry Lectures at Yale and stated that students must understand the tactics and strategies of science, an obvious reference to NOS. He later expressed the view that "some understanding of science by those in positions of authority and responsibility as well as by those who shape opinion is therefore of importance for the national welfare" (1947, p. 4). Conant (1951) later expanded on these ideas by suggesting that "every American citizen … would be well advised to try to understand both science and the scientist as best he can" (p. 3). These are among the earliest and most clearly stated rationales for the inclusion of nature of science as an essential part of science literacy in the United States. Even if the term *nature of science* was not widely used, it is clear that is what these early advocates mind.

The 1957 Soviet launch of Sputnik and the perceived threat to US superiority in science and technology gave rise to what has been called the *Golden Age of Science Education*. During the period following Sputnik extending through the 1960s, various US government agencies funded a large number of projects targeting the improvement of science and mathematics education with study groups and a staggering number of curriculum development projects. These were all designed to bolster the nature and effectiveness of science and mathematics teaching in the nation (DeBoer 1991).

By 1960, the National Society for the Study of Education argued even more clearly for the inclusion of NOS in school science:

> There are two major aims of science-teaching; one is knowledge, and the other is enterprise. From science courses, pupils should acquire a useful command of science concepts and principles. Science is more than a collection of isolated and assorted facts . . . A student should learn something about the character of scientific knowledge, how it has been developed, and how it is used. (in Hurd 1960, p. 34)

An additional justification for the inclusion of the nature of science in science class comes from science educator Joseph Schwab (1964), who correctly observed that science is taught as an "unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24). Many of the science curriculum projects of the 1960s – sometimes called alphabet soup projects because of their letter-rich acronyms (such as S-APA, ESS, CHEM Study) – were designed to shift science instruction away from a focus on "what do scientists know" (i.e., content) to an examination "how do scientists know" (i.e., process). Interestingly, several of the science curriculum projects funded by the government as a response to the perceived Soviet threat were expressly designed with NOS elements so that students would have the opportunity to understand how to "do" science in the real world. Of course, this is hardly a surprise since the expressed purpose of these new curricula was to encourage more students to become scientists and engineers.

As the 1960s became the 1970s, several authors reminded science educators of the importance of the nature of science by using that term expressly. Robinson (1968) in *The Nature of Science and Science Teaching* discussed the nature of physical reality including probability, certainty, and causality and concluded with by considering the interplay between science instruction and the nature of science. In *Concepts of Science Education: A Philosophical Analysis*, Martin (1972) reiterated some of these arguments in support of including NOS in science instruction by advocating the use of inquiry learning along with discussion of the nature of explanation and the character of observation in the science classroom.

NOS studies gained traction in the final decades of the twentieth century. There were contributions to NOS studies from increasing numbers of scholars, focused publications in the field and increased advocacy and understanding for the place of the history and philosophy of science in the science classroom. At this same time Duschl (1985) reminded the science education community that the way science was increasingly represented in classrooms was often at odds with a modern view of how science functions.

Next, various organizations in the United States such as the National Research Council (NRC) and the American Association for the Advancement of Science (AAAS) expressed interest in the nature of science. AAAS released an important report defining what literate individuals should know about science, called *The Liberal Art of Science: Agenda for Action* (AAAS 1990). It featured an entire chapter with recommendations for what sort of NOS topics ought to be included in school science. These included science values and ways of knowing, methods of collecting, analyzing and classifying data, the nature of explanations in science, and the limits on scientific understanding.

Without NOS, students will very likely continue to see science only in its "final form," a label coined by Duschl (1990) describing the situation in which students learn only the conclusions of science with little opportunity to experience how these scientific discoveries were made. "Final form science" provides such a shallow view of the scientific enterprise that students are unable to use the methods of science for themselves or to gauge the scientific worth of ideas proposed by others.

61.4 Why Nature of Science Matters: The United States Context

At this point it is important to recognize a special challenge with respect to NOS in US classrooms. Certainly, NOS can help students understand and appreciate the inner workings and limitations of science as a way of knowing. With that goal in mind, it would be hard to imagine than anyone would argue with its inclusion in science class, particularly if NOS knowledge assists science learners become better decision makers on scientific matters.

However, this is precisely why NOS is needed and why some might rather omit it. If students can judge the worth of scientific evidence and conclusions on their own, they will be far less likely simply to accept what others tell them. This has become an important issue with respect to topics perceived as controversial by some in the United States. such as evolution and, more recently, climate change. If students understand how science functions, they would quickly realize that issues like these are not just matters of opinion. In fact, they are matters of science not politics, not religious doctrine, and most certainly not just opinion. If the scientific evidence demands reaching a particular conclusion, then that is the most reasonable conclusion to accept even if it is unpalatable for some external reason like religion, politics, or preference.

As a case in point, consider the case of biological evolution and those who reject it because of their motivation by a particular worldview (Moore et al. 2009). Evolution denial has been active for more than a century; since education was governed locally for much of the history of the United States, evolution was simply not taught as too heretical. Following the famous 1925 Scopes trial in the southern state of Tennessee, there was a national debate about the teaching of evolution that generally left evolution out of most science classrooms. Space does not permit a full account of the battles in both courthouses and the court of public opinion, but even the last major skirmish which occurred probably will not end the attacks. In 2005, the Dover Area School District in Pennsylvania lost an expensive and foolish fight to defend their policy requiring the teaching of intelligent design along with evolution as an "alternative" in biology class (Humes 2007).

It is not clear if those who deny evolution and climate change are sophisticated enough to understand that when students have the tools to think for themselves they will either accept or reject scientific ideas based on the merits of the ideas themselves rather than with reference to some preformed ideology. Perhaps the long tradition of democracy in the United States has caused some to think that we can and should vote on everything including the validity of scientific ideas. If students and their parents fail to understand the guiding principles of science, they may think that all knowledge from any source is essentially a matter of opinion, and therefore, equally valid. This relativistic approach has given rise to the "science wars," which are a subset of the greater "culture wars" that have raged in some decades. Such "wars" result either when one group feels excluded by the knowledge generation methods and traditions of another or when a group assumes the position that no source of knowledge – including science – produces more secure results than any other (Parsons 2003; Brown 2001). Students are the causalities of these "wars" when important elements of the curriculum are eliminated or minimized or even mocked. This happened with evolution and is occurring with climate change.

The battle against evolution and the growing rejection of global warming have shared roots in a lack of understanding of how science functions. A firm appreciation of the limits of science should enable those who question evolution to recognize that its acceptance does nothing to negate most religious beliefs. Those who reject climate change on ideological grounds will be much less likely do to so if they understand that science forms conclusions not on the opinions of a few but on the preponderance of the evidence as analyzed and interpreted by the community of scientists worldwide. Only through knowledge of the nature of science can students understand how science produces and validates knowledge. Given the continuing tensions about the process and products of science in the United States, knowledge of NOS is arguably more important here than in almost any other nation. With that thought in mind, we can turn our attention to what aspects of the nature of science should inform science teaching and learning.

61.5 Nature of Science in US Science Education Standards Documents

Many involved with science education in the United States would likely agree with a decision to call the recent decades as the *Age of Standards* in science education. In a relatively short time two documents were designed to guide the teaching and learning of science at a national level. Of course, some states already had their own documents, but the advent of the national standards movement gave rise to the development of the first major sets of science standards. Interestingly, two documents from two different groups – with some overlap in committee membership – appeared almost simultaneously.

The first of these came from the American Association for the Advancement of Science (AAAS)-sponsored *Project 2061* (1989) (designed to reform science teaching by the time Halley's Comet returns in 2061) and the related *Benchmarks for Science Literacy* (AAAS 1993). Just 3 years later, the National Research Council released its own proposal for the content of school science boldly titled the *National Science Education Standards* or *NSES* (NRC 1996). In spite of a high degree of similarity between them, the *Standards* made the recommendation that science should be taught through inquiry, while *Benchmarks* is generally silent on how science should be taught. Of course, given the issue of educational governance in the United States, neither set of guidelines could be imposed and, in fact, no state fully adopted all of the recommendations.

A detailed comparison of *NSES* and *Benchmarks* (McComas and Olson 1998) revealed that both documents provided many targeted recommendations regarding the nature of science for K–12 science instruction. Both documents generally describe how science functions and builds new knowledge by mentioning the common characteristics of science including the use of careful measurement, observation, experiment, peer review, and potential for replication. Science is labeled as tentative, calling theories and laws as related but distinct aspects of science; science is portrayed as a collaborative and social human endeavor affected by the social and historical milieu within a domain of creativity. Neither document provided as complete a description of science for science teaching as recommended by Lederman (2002, 2007), McComas (1998, 2008), and Osborne and colleagues (2003). However, the strong NOS message in these two documents affirmed the nature of science as a necessary part of the science teaching enterprise that could no longer be ignored.

So, the debate about *whether* to teach NOS has ended leaving open only the question about *what* NOS elements should be taught. The response to this challenge may best be achieved by using the consensus approach which considers the common views of various science education experts. Some, such as van Dijk (2011), reject the consensus approach for making this determination partially on the grounds that the final picture that emerges is not a complete view of NOS. Perhaps, but this is no more or less true than the consensus about what to teach that resulted from an examination of traditional science topics such as chemical reactions, photosynthesis, and the rock cycle. Anything we teach students about science and its nature should be accurate with respect to the needs and abilities of the target audience. However, the goal in defining what NOS to teach in schools is predicated on what students need to appreciate the scientific enterprise, what they can understand, and what the curriculum can support, not in providing an obsessively complete view of the nature of science as known by historians and philosophers of science.

One particularly fruitful approach about what NOS to teach is found in an analysis of science standards from each of the US states. These documents can be seen as quasi-independent opinions (of course, many of those who crafted these documents reviewed the foundation same literature) on NOS that allow us to reach some common ground on what elements of the nature of science should best inform school science teaching.

61.6 Nature of Science in the US State Science Standards

The US state science teaching standards have traditionally been in flux both due to the ongoing cycle of revision and updating. This change will continue because most of the state science standards will disappear as the new standards are adopted. Therefore, an analysis of the existing standards just before the adoption of the *Next Generation Science Standards* can provide both an interesting historical review and a rich picture of NOS instruction in the United States with great potential for reaching agreement on the nature of science in schools.

McComas and colleagues (2012) reviewed the then-current science content standards of the 50 US states and the District of Columbia (N = 51) to determine what NOS content was included. The investigation was focused on a search for the appearance of any of 12 elements of the nature of science[1] most commonly recommended by experts (Al-Shamrani (2008). These are called key aspects of NOS and detailed as a part of Table 61.1.

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[1] The 12 key NOS elements were used to guide the search, but researchers were attentive to and noted all instances of NOS-related language found in thousands of lines of text in 51 documents. In these documents, more than 3400 instances of NOS were located and categorized.

Table 61.1 The percentage of US state standards documents in which specific key aspects of the nature of science appears at least once (N = 51)

Key aspects of NOS found in a review of all US state standards documents in the spring of 2012 (N = 51)	Percentage of state standards documents in which specific aspects of NOS appear (%)
Science is based on empirical evidence	96
Cooperation exists in science	90
Scientific conclusions have a degree of tentativeness	90
Distinction between observation and inference	86
Role of experiments in science	86
Distinction between science and technology	84
Science is socially and culturally embedded	76
There is no stepwise scientific method	71
Science has a subjective element	61
Distinction between law and theory	55
Science cannot answer all questions (i.e., there are limits to science)	49
Creativity has a role in science	25

Each appearance of NOS was noted to (a) identify which NOS elements appear, (b) gauge where they appear with respect to educational level (elementary, middle, and secondary), (c) determine how many of the key elements are included (this is called completeness), (d) measure the distribution or comprehensiveness of NOS elements with respect to their inclusion in and across grade levels, and (e) rank the state standards documents based on a combined measure of completeness and comprehensiveness. In brief this analysis provides an in-depth look at NOS in US public schools just before the introduction of new science instructional standards.

61.6.1 Nature of Science in the US State Standards

Table 61.1 reports the specific key NOS elements that appear in the science standards of each state; data provided next will provide much more detail about where the NOS element appears with respect to grade level and with what frequency. These data reveal which key NOS elements (empiricism, tentativeness in science, cooperation and collaboration in science, the distinction between observations and inferences, and the role of experiments) are included within the standards of most states. From this review, creativity, the idea that science cannot answer all questions, and the distinction between law and theory are shown to be included less frequently than other notions in the state science standards.

Table 61.2 The US states listed with the number of key NOS aspects included in their science content standards along with a "letter grade" associated with that number of key aspects of NOS

Score	Number of key aspects of NOS included	State
A+	12	NE, NH, NC, OH
A	11	FL, IN, KY, ME, MI, MN, MO, NV, NJ, NY, OR, TN
B	10	AK, GA, KS, LA, MA, MS, NM, ND, DC
C	9	ID, IL, MD, VA, WA, WV
D	6–8	AL, AZ, AR, CA, CO, HI, MT, OK, PA, SD, UT, VT, WI

61.6.2 Which US State Standards Contain the Most NOS Elements?

The data in Table 61.2 show how likely it is that a state document would include a complete range of all recommended NOS elements. Sixteen states rate highly in terms of completeness; some states (Nebraska, New Hampshire, North Carolina, and Ohio) have all 12 key NOS elements in their science content standards.

61.6.3 The Nature of Science Recommendations for Grade Level in the US State Standards

The empirical aspect of science, the role of cooperation, the distinction between observation and inference, and the distinction between science and technology are the most likely NOS elements to be found across grades K–12. Creativity and the distinction between theory and law are introduced only at the higher grade levels (Table 61.3).

61.6.4 Combining Completeness and Comprehensiveness: How Do the States Rank for NOS Inclusion?

Using a weighted system by which states earn "high marks" for having the most NOS elements included most frequently *across* grade levels, we ranked each state based on how NOS is featured in its science teaching standards. This ranking system is based on determining a top score in which all of the NOS elements would appear in the standards at every grade level. However, achieving this top score is not anticipated or even advocated since some NOS elements might be inappropriate for younger learners. Therefore, the final analysis was a norm-referenced scale that reveals what states thought was possible rather than for the researchers to suggest

Table 61.3 The percentage of state documents in which each key aspect of the nature of science appears generally (N = 51) and appears at a particular grade-level span

Key aspects of NOS found in US state standards	Percentage of documents in which the NOS element appears	Percentage of state documents in which a NOS element (sub-domain) appears at a particular grade level span as a measure of comprehensiveness			
	(%)	Grades K–2 (%)	3–5 (%)	6–8 (%)	9–12 (%)
Science is based on empirical evidence	96	59	88	78	80
Cooperation exists in science	90	63	71	80	84
There is a tentative element in science	90	24	41	73	67
Distinction between observation and inference	86	51	65	55	57
Role of experiments	86	27	69	76	71
Distinction between science and technology	84	59	73	73	67
Science is socially and culturally embedded	76	35	51	55	63
There is no stepwise scientific method	71	22	43	57	57
Science is somewhat subjective	61	14	35	47	43
Distinction between law and theory	55	4	16	33	47
Science cannot answer all questions (i.e., there are limits to science)	49	39	39	35	37
Creativity play a role in science	25	6	10	16	14

what was ideal. Space limitations preclude including the results for each state, but Tables 61.4 and 61.5 provides the norm-referenced ranking of those states that scored highest when considering both completeness and comprehensiveness.

Not unexpectedly, no state suggested that all of the key NOS elements should be included at every age/grade level. If we treat the 50 states as independent experiments in writing NOS-related standards, we can learn much about consensus and innovation. For instance, it is possible to note that some of the NOS elements are more likely to be recommended for younger students, while other NOS content is generally reserved for those in the upper grades. This is an important consideration in the design of science curricular.

Not surprisingly, there is a huge variance in terms of NOS inclusion when comparing the fifty-one US science content standards. The authors of this study found that many states include both a complete picture of recommended NOS content and do so across grade levels. This strategy of returning to content repeatedly at higher

Table 61.4 States within the top 10 ranks with respect to completeness and comprehensiveness taken together (Note: some states' ranks were tied with others for their rank so the list does not extend to 51)

Highest rank with respect to NOS completeness and comprehensiveness in the state standards	State
1	OH
2	FL, NH, OR
3	MO
4	NC
5	KY, NJ
6	NE
7	MI, NY
8	MA
9	MN
10	LA

Table 61.5 States within the lowest 10 ranks with respect to completeness and comprehensiveness taken together (Note: some states' ranks were tied with others for their rank so the list does not extend to 51)

Lowest rank with respect to NOS completeness and comprehensiveness in the state standards	State
31	AZ
32	CA
33	WI, AR
34	DE, WY
35	TX
36	AL, CO
37	CT, SD
38	SC
39	RI
40	IA

levels of abstraction and/or complexity across grade levels is an excellent application of the spiral curriculum in instructional design. Some of the recommended NOS elements are complex enough that students would learn little from a one-time encounter. NOS is so integral to an understanding of the scientific enterprise that including some elements only at one grade level or only at a particular time in the science curriculum would reduce the likelihood that students would understand the concept and appreciate its significance. So, those states that expect students to engage NOS content early and often are to be congratulated.

However, as with everything else of importance in the educational enterprise, actual NOS instruction in classrooms is in the hands of teachers. No matter how robust the state standards are, such standards are embraced and interpreted by the 7.2 million teachers in 15,000 school districts across the nation (US Census Bureau 2011). What NOS instruction looks like in one classroom may be quite distinct from such instruction in another classroom, even in the same school.

This analysis of the multiplicity of guidelines produced in the last decade demonstrates that NOS is important and that there is a consensus among science educators and policymakers toward what elements of the nature of science are most appropriate to inform school science instruction (see Table 61.1). Furthermore, the analysis has also provided evidence of which particular NOS aspects are most appropriately included at each grade-level span (Table 61.3). Such data are of vital importance in designing future science standards guidelines.

61.7 Nature of Science: An Emerging Consensus View

Figure 61.1 is a graphical organizer of a consensus view of the nature of science designed to inform school science. This plan is based on a review of the prevailing experts, a review of the fifty-one US state documents (McComas et al. 2012) and earlier suggestions from McComas (2008).

Here, the nine recommended elements of the nature of science are arranged in three suites of related items: the tools and products of science, science knowledge and its limits, and the human elements of science. Nine domains or key aspects of NOS (empirical basis, shared methods, subjectivity, creativity, and others) are not suggested as complete descriptions. Also, when elucidated and discussed, it will be obvious that some of these nine are more extensive in scope and content than others. For instance, the NOS element "science has shared methods" relates to a range of issues including the ideas that there is no single step-by-step method and that scientists share techniques such as good record keeping and use of induction, deduction, and inference. On the other side of the figure, we find the distinction between science and technology noted. This is a relatively discrete idea stating that students should understand the distinction between the roles and processes of science and those of technology and engineering. Such distinctions are more important than ever given the inclusion of engineering in the *Next Generation Science Standards*. The point to keep in mind is that the "size" of each other nine recommendations is

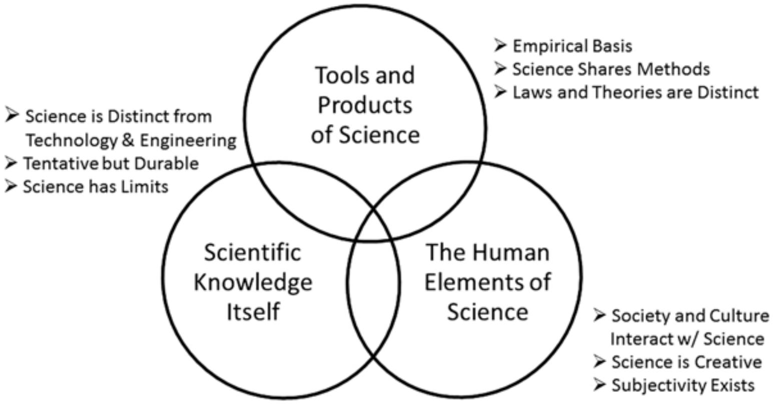

Fig. 61.1 A graphical representation of nine basic NOS elements frequently recommended for use in K-12 science instruction, arranged into suites of related items (Adapted from McComas (2008))

not the same nor is the level of complexity of the underlying idea. Textbook authors, curriculum designers, and, of course, teachers will ultimately be responsible for how these ideas are integrated into classroom instruction.

Figure 61.1 is nothing more than a potentially useful way to illustrate the range and relationship of the NOS elements most commonly recommended to inform and enliven science teaching in schools. There should be no implication that these elements are simply to be memorized on the first day of school and quietly forgotten. Rather, these elements must be explicitly explained, illustrated with examples, mentioned in context with discussion of science content, and assessed to gauge student understanding.

61.8 The Next Steps in US Science Instruction: The Framework for K-12 Science Education and the Next Generation Science Standards

One of the challenges with respect to providing an overview of the nature of science in the US context is that change in the educational landscape is constant. This is particularly true now that many of the US states are poised to adopt shared new science instructional standards, presumably abandoning their specific state learning goals. Colleagues in mathematics and English/language arts education have already faced this situation. Many of the US states have accepted what is called the "Common Core" (*Common Core State Standards for English Language Arts & Literacy in History/Social Studies, Science, and Technical Subjects*), a set of shared instructional standards in these disciplines (Council of Chief State School Officers 2010; Rothman 2011). Also, students are to develop appropriate levels of writing and reading literacy in the content area of science.

The latest revolution in science instruction in the United States began with the release of a new document designed to guide science teaching at the precollege level titled *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council 2012). The recommendations in the *Framework* have already been transformed into various draft versions of the *Next Generation Science Standards (NGSS)* which, in turn, have been reviewed by working groups across the nation. As is often the case when it comes to shared initiatives, a few states have decided not to endorse the *Next Generation Science Standards*, so some diversity in the nature of the US science curriculum will continue to exist. However, the vast majority of US states plan to adopt the *NGSS* recommendations thus shifting the balance of power in education, in a curricular sense, quite dramatically.

61.8.1 A Framework for K-12 Science Education

Since the *Framework* (NRC 2012) represents a major new source of thinking about science teaching in the United States, it will be examined in detail with respect to its

Table 61.6 The three dimensions of the Framework for K-12 Science education: practices, crosscutting concepts, and core ideas (NRC 2012, p. 3). One example from each disciplinary core idea is provided as an illustration, but there are many more

1. Scientific and engineering practices
    1. Asking questions (for science) and defining problems (for engineering)
    2. Developing and using models
    3. Planning and carrying out investigations
    4. Analyzing and interpreting data
    5. Using mathematics and computational thinking
    6. Constructing explanations (for science) and designing solutions (for engineering)
    7. Engaging in argument from evidence
    8. Obtaining, evaluating, and communicating information
2. Crosscutting concepts
    1. Patterns
    2. Cause and effect: mechanism and explanation
    3. Scale, proportion, and quantity
    4. Systems and system models
    5. Energy and matter: flows, cycles, and conservation
    6. Structure and function
    7. Stability and change
3. Disciplinary core ideas
    - Physical science (such as matter and its interactions)
    - Life sciences (such as from molecules to organisms; structures and processes)
    - Earth and space science (such as Earth's place in the universe)
    - Engineering, technology, and applications of science (such as engineering design)

inclusion of aspects of the nature of science. The Framework is a narrative result of discussions from expert groups empaneled to ensure accurate science content and provide a set of broad expectations for science and engineering education in the K-12 learning environment. The *Framework* provides recommendations in three domains including science and engineering practices, crosscutting concepts, and core ideas in life, physical, and Earth/space sciences. Although engineering and technology were mentioned in previous standards documents, engineering has risen to a status almost equal to that of science itself. In fact, the *Framework* is endorsed by the presidents of the National Academy of Sciences *and* the National Academy of Engineering.

Since these three dimensions are inherent in the design of the *Framework* and to the new standards, it is useful to include them here (Table 61.6). Some of these dimensions do relate to elements of the nature of science, but it is important to note that NOS itself does not appear explicitly even though "how science works" could certainly be considered a crosscutting concept.

A number of techniques were used to analyze the *Framework* for its inclusion of NOS elements including the application of the new computer search tool (Jiang 2012) specifically developed to look for inclusions of specific content in large digital files. In addition, the search examined the index in the *Framework and* performed keyword searches within the *Framework*, accompanied by a reading of the *Framework* to establish context.

The computer-assisted search found that most of the major recommended ideas in the nature of science appear in the *Framework.* Of course this is encouraging. However, a closer examination of the document reveals that although NOS is stated and implied at various places in the text, but not explicitly recommended anywhere. The key NOS concepts are scattered throughout the document rather than being located in one section, and only a few appear in the index. Even the term "nature of science" only appears in the index (science, nature of) in a discussion of recommendations for improvement to the *Framework*. This is curious considering the following strong statement:

> any [science] education that focuses predominately on the detailed products on the detailed products of scientific labor—the facts of science—without developing an understanding of how those facts were established or that ignores the many important applications of science in the world misrepresents science . . (NRC 2012, p. 43)

As a way of considering what the *Framework* contains with respect to the nature of science, these next few sections will examine how the NOS concepts of creativity, scientific method, inference, law/theory, tentativeness, limits of science, subjectivity, and the social elements of science are treated in the *Framework.* It is particularly noteworthy to see how widely scattered the references are and how diligently one would have to search the entire *Framework* and infer in order to derive a useful recommendation for nature of science.

61.8.2 Creativity in the Framework

Most experts agree that creativity is an important part of science, and the *Framework* mentions this fact in the following places: "They [students] should come to appreciate that science and the current scientific understanding of the world are the result of many hundreds of years of creative human endeavor" (NRC 2012, p. 9). "Not only is such an approach alienating to young people, but it can also leave them with just fragments of knowledge and little sense of the creative achievements of science, its inherent logic and consistency, and its universality" (NRC 2012, p. 10). "…the insights thus gained help them [students] recognize that the work of scientists and engineers is a creative endeavor—one that has deeply affected the world they live in" (NRC 2012, pp. 42–43). "…construction of explanations or designs using reasoning, creative thinking, and models" (NRC 2012, p. 44), and "the creative process of developing a new design to solve a problem is a central element of engineering" (NRC 2012, p. 206).

61.8.3 Scientific Method in the Framework

The notion that there is no single stepwise scientific method appears in the *Framework* in a variety of places, but there is no single description of what this means, nor is the term found in the index. Consider the following statements: "Second, a focus on practices (in the plural) avoids the mistaken impression that there is one distinctive approach common to all science – a single "scientific method" – or that uncertainty is a universal attribute of science" (NRC 2012, p. 44). "For example, the notion that there is a single scientific method of observation, hypothesis, deduction, and conclusion—a myth perpetuated to this day by many textbooks—is fundamentally wrong" (NRC 2012, p. 78). "Thus the picture of scientific reasoning is richer, more complex, and more diverse than the image of a linear and unitary scientific method would suggest" (NRC 2012, p. 78) and "…and not as rote procedures or a ritualized 'scientific method'" (NRC 2012, p. 254). All of these statements accurately represent the issue related to "scientific method" correctly and appropriately, but the new Framework focuses on science and engineering practices, and the way in which those practices are discussed together in the document could be a source of new misunderstandings about this issue.

61.8.4 Law/Theory in the Framework

For decades, educators have been concerned that students do not understand the relationship between hypothesis, theory, and law. The *Framework* has a multitude of references to the term "hypothesis," several to "theory," but no direct references to the role of law in science. There are the following implied references to "law," but it is not clear why the term itself is missing.

With respect to laws, the *Framework* offers the following: "Repeating patterns in nature, or events that occur together with regularity, are clues that scientists can use to start exploring causal, or cause-and-effect, relationships, which pervade all the disciplines of science and at all scales" (NRC 2012, p. 87). The following statement comes close to providing a definition of "law," but unfortunately it is not referenced in the index:

> One assumption of all science and engineering is that there is a limited and universal set of fundamental physical interactions that underlie all known forces and hence are a root part of any causal chain, whether in natural or designed systems. Such "universality" means that the physical laws underlying all processes are the same everywhere and at all times; they depend on gravity, electromagnetism, or weak and strong nuclear interactions. (NRC 2012, p. 88)

There is a very well-constructed discussion of hypotheses and laws in the *Framework*, a section of which is shown below. Unfortunately, the obvious and necessary link to "law" is absent.

> Theories are not mere guesses, and they are especially valued because they provide explanations for multiple instances. In science, the term "hypothesis" is also used differently than it is in everyday language. A scientific hypothesis is neither a scientific theory nor a guess; it is a plausible explanation for an observed phenomenon that can predict what will happen in a given situation. (NRC 2012, p. 67)

61.8.5 Tentativeness in the Framework

Finally, we consider the idea of tentativeness in the *Framework*. In addition, we find a few statements about this issue such as “any new idea [in science] is tentative …” (p. 79) and “any new idea is initially tentative, but over time, as it survives repeated testing, it can acquire the status of a fact—a piece of knowledge that is unquestioned and uncontested, such as the existence of atoms” (p. 94). Unfortunately, there are problems with both of these statements. In the first case, there is no corresponding statement about how long-lasting (or durable) science knowledge is in practice even if it is tentative. In the second case, the statement is incorrect because it implies that once a “fact” is established, its tentative character is somehow eliminated. Philosophers of science would remind us that all knowledge in science is tentative.

61.8.6 Limits of Science and Subjectivity in the Framework

These important issues are neglected in the *Framework*. There are many mentions of the targets of science and engineering but there is no explicit statement about what science and engineering cannot do. Unless one has a strong background in the philosophy of science, it would not be intuitively obvious that science does not address all problems in all domains. This is a particularly troublesome issue since many students fail to understand that many of their religious notions are not in the domain of science and therefore are not subject to attack by science. In the case of evolution, for instance, students would be well served by knowing that the scientific explanation of biological change through time does not demand that they give up a belief in some metaphysical component to such change.

There are vague implications in the *Framework* that science has subjective elements, but the word appears nowhere in the document. This is unfortunate, because an examination of the history of science provides many examples of how scientists have personally pushed and rejected ideas and interpreted evidence even contrary to the views of others. Sometimes this subjective element is exactly what was necessary for an idea finally to be accepted by the scientific community (i.e., Milliken’s discovery of the charge on the electron). Giving students opportunities to recognized that science has a subjective element is valuable in portraying science accurately and situating science as a human pursuit.

61.8.7 Science as a Social Activity in the Framework

There are a number of references in the *Framework* to the social aspect of science. Consider the following as a good description of this aspect:

> . . . science is fundamentally a social enterprise, and scientific knowledge advances through collaboration and in the context of a social system with well-developed norms. Individual scientists may do much of their work independently or they may collaborate closely with colleagues. Thus, new ideas can be the product of one mind or many working together. (NRC 2012, p. 26)

The only objection to this phrase relates to its placement. As is the case with many of the NOS elements in the Framework, this one is not included along with other nature of science ideas so that readers could see this as part of a broader description of NOS in science education.

61.8.7.1 The Framework and NOS: Conclusions and Concerns

The *Framework* does contain some meaningful suggestions for the nature of science and even includes a section called "understanding how scientists work" with the following powerful statement reproduced here in full:

> The idea of science as a set of practices has emerged from the work of historians, philosophers, psychologists, and sociologists over the past 60 years. This work illuminates how science is actually done, both in the short term (e.g., studies of activity in a particular laboratory or program) and historically (studies of laboratory notebooks, published texts, eyewitness accounts). Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions, specialized ways of talking and writing, the development of models to represent systems or phenomena, the making of predictive inferences, construction of appropriate instrumentation, and testing of hypotheses by experiment or observation.
>
> Our view is that this perspective is an improvement over previous approaches in several ways. First, it minimizes the tendency to reduce scientific practice to a single set of procedures, such as identifying and controlling variables, classifying entities, and identifying sources of error. This tendency overemphasizes experimental investigation at the expense of other practices, such as modeling, critique, and communication. In addition, when such procedures are taught in isolation from science content, they become the aims of instruction in and of themselves rather than a means of developing a deeper understanding of the concepts and purposes of science. (NRC 2012, p. 43)

Unfortunately, what the *Framework* fails to do is to clearly and explicitly feature exactly what NOS elements are recommended and provide some definitions and descriptions in one place to serve as a useful guide for those hoping to use the document to frame instruction in this important area. The NOS suggestions are implied, too widely scattered and much too implicit to be of use to educators not already familiar with the nature of science. To profit from the *Framework*, educators would have to work very hard and infer much to derive a useful list of NOS goals, a task that would be difficult without considerable expertise in this area. It is ironic that the document reports that "Many of those who provided comments thought that the "nature of science" needed to be made an explicit topic or idea. They noted that it would not emerge simply through engaging with practices" (NRC 2012, p. 334). It is curious that the authors had to be informed of this clear fact.

61.8.7.2 The Next Generation Science Standards and the Nature of Science

Following the release of the *Framework*, committees began the development of the *Next Generation Science Standards (NGSS)* with a March of 2013 target date for

Table 61.7 An example of the first of the content standards from the next generation science standards (NRC 2013) showing the link to the nature of science associated with that standard

Section title: K. forces and interactions: pushes and pulls	
Specific goals:	K-PS2-1. Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object K-PS2-2. Analyze data to determine if a design solution works as intended to change the speed and direction of an object with a push or pull
Science and engineering practices:	Planning and carrying out investigations Analyzing and interpreting data
Disciplinary core ideas:	PS2.A: Forces and motion PS2.B: Types of interactions PS3.C: Relationship between energy and forces ETS1.A: Defining and engineering problem
Crosscutting idea: Patterns and cause and effect	
Nature of science: Scientific investigations use a variety of methods	

completion. What makes this document different from others is that almost all of the states agreed to use this single set of guidelines to guide science teaching. Another major change is that the NGSS would be based on the science and engineering practices, core ideas, and crosscutting concepts (see Table 61.6) in addition to a blending of science with engineering. The goal of these new standards is that all high school graduates would have enough knowledge of science and engineering to participate in debates about science issues, make informed choices as consumers, and be prepared to enter science-related careers.

Various groups and individuals reviewed the *Framework* and agreed that it failed to adequately illustrate and define the various elements of the nature of science that should inform science teaching. What resulted from this review is a much more robust and complete vision for NOS in the NGSS with eight specific NOS domains discussed in an appendix and included throughout the document. Each domain of grade-level content is linked to the other design elements, but now the nature of science is explicitly included. Consider the following example from the NGSS illustrated in Table 61.7.

Unlike in the *Framework* where the nature of science elements is highly scattered, those in the *Next Generation Science Standards* (NGSS) are found together in a single appendix. There are eight NOS categories each with specific learning goals divided into recommendations for K–2, 3–5, middle school, and high school learners. Table 61.8 includes all of these NOS recommendations along with a description of that learning goal. The authors also indicate that some of the NOS goals are most closely associated with science and engineering practices and some with the crosscutting concepts. While it is not clear why this is important, perhaps the authors hope that teachers will be able to teach aspects of NOS while teaching some of the other recommended content.

Table 61.8 Categories of nature of science found in Appendix H of the next generation science standards (NRC 2013). Additional detail provided has been extracted from the specific details associated with the learning goals stated for each of the grade level (K–2, 3–5, middle, and high school). Those goals thought to be most associated with science and engineering practices are labeled Pr, and those most closely linked to crosscutting concepts are labeled Cr

Scientific investigations use a variety of methods (Pr); this implies that there is no step-by-step method, but this is not stated, that students are to distinguish between science and nonscience, and that scientists share values such as objectivity and open-mindedness

Scientific knowledge is based on empirical evidence (Pr); the grade-level expectations for this NOS element are much the same and self-evident that science requires evidence

Scientific knowledge is open to revision in light of new evidence (Pr); this implies that science is tentative but this is not stated explicitly

Science models, laws, mechanisms, and theories explain natural phenomena (Pr); theory and law are said to be individual and unique elements of science. Useful and accurate definitions are provided

Science is a way of knowing (Cr); additional information relates to the unique elements of science (such as empiricism and skepticism) and the view that scientific modes of inquiry can be used by sciences and nonscientists and that contributions to science come from various types of people

Scientific knowledge assumes an order and consistency in natural systems (Cr); this notion relates to an expectation that nature is orderly and develops this idea across the grade levels

Science is a human endeavor (Cr); all types of people have contributed to science and continue to make contributions and that science influences and is influenced by society. Other issues mentioned include creativity, some discussion of science, and its link to technology

Science addresses questions about the natural and material world (Cr); the NOS category includes discussion of the target of science, the notion that science cannot answer all questions, and the role of science in decision-making

The way in which these eight NOS ideas are linked to the specific learning objectives seems more of an afterthought than something strategic, but this reviewer is pleased to see NOS represented so prominently. In the example provided earlier (Table 61.7), please note that the NGSS considers that when young students learn about “forces and interactions,” this would be a good time to demonstrate that “scientific investigations use a variety of methods.”

61.8.8 Next Generation Science Standards: Conclusions and Critique

There is no doubt that the authors of the *NGSS* responded appropriately to the comments made by those who reviewed the *Framework*. The nature of science goals is more explicitly stated and organized. However, there are still some issues regarding NOS of some concern. These include the perception that some of the ideal NOS elements are missing, the nature of the narrative justifying NOS in the NGSS Appendix, the placement of NOS in the *NGSS*, and the potential challenges associated with potential conflating of science and engineering in the minds of students.

With respect to what is missing, the most glaring omission is an explicit statement indicating that science advances both through organized means and through somewhat subjective ones. It would be reasonable to include this in the category of "science is a human endeavor." Creativity should be mentioned more consistently. Currently, the ideas of "creativity and imagination" are noted only as grades 3–5 and high school goals within the human dimension category. Of course, it is reassuring to see this characteristic of science listed at all, but there is little reason for its lack of prominence. It would be useful to discuss the relationship of tentativeness and durability across grade levels rather than saving such discussion only for high school students. The *NGSS* standards are silent on the distinction between inference and observation, an issue that could be easily corrected in either of the first two categories, "variety of methods" or "empiricism."

Since the *Standards* include engineering goals along with those for science, one would have expected to see a NOS goal statement distinguishing science from technology and engineering. Formally, suggestions to include this NOS element had not been embraced by the science education community, but must now rise in importance because of the curious design of the *NGSS*. The *NGSS* and its blend of science and engineering present the danger that students may consider science and engineering as similar, therefore confuse the two. These two disciplines are not the same; they have distinct goals and distinct methods, and although there are advantages in blending scientific ideas with their application through engineering, educators must work very hard to distinguish one from the other.

In conclusion, two other concerns about NOS in the NGSS come to mind. First, the rationales, research, and proposed instructional mechanism for NOS provided in Appendix H are remarkably shallow. The brief section discussing the development of NOS is incomplete; there has been significant work done in recent decades to justify the inclusion of NOS but that has not been included in any strategy or complete fashion. For instance, the use of history as a means by which NOS may be included in the classroom is fine, but there are many other ways to integrate nature of science and science teaching, yet the *NGSS* offer no other suggestions. The two charts listing the key NOS elements are very well designed, but they offer a learning progression for teaching aspects of NOS across the grade levels that does not seem to have been based on a review of the research. Finally, the positioning of the NOS links at the bottom of each page of science content goals makes it appear that NOS was an afterthought. All those who recognize that NOS is fundamental to students' understanding of the scientific process will have to redouble efforts to ensure that reality prevails as the national embraces these new science standards.

61.9 Standards and the Nature of Science: Challenges and Conclusions

In the United States there is no mechanism yet in place to guarantee that any particular science content, including NOS, is taught in each classroom in an appropriate and complete manner. Having well-reasoned standards is a very good step, but issues of assessment, teacher preparation, and targeted curriculum approaches to teaching the nature of science are also important.

61.9.1 Assessment and the Nature of Science

Through national legislation known as *No Child Left Behind*, the US federal government has mandated that some science content acquisition be measured by end-of-course (EOC) evaluations. However, presently there is no single measure applied nationally and few of the state-developed instruments measure much that could be considered related to the nature of science. This situation may change with the widespread adoption of the *Next Generation Science Standards*. When the majority of US states are using the same science teaching standards, it will become increasingly cost-effective to produce assessment tools for use widely. Such assessments become a powerful "policy lever" to encourage teachers to include any specific content in instruction. Of course, this content must include the nature of science.

Although there is now an increasing consensus on what aspects of NOS should be communicated in school settings, the problem of assessment has not yet been fully addressed. We simply do not have valid, reliable, and complete measures of NOS that can be administered to large groups of students and scored quickly in a cost-effective manner. We are also still grappling with important considerations such as how contextualized any measures of NOS must be to be valid. In other words, must NOS items in a biology end-of-course test be different markedly from those used for physics students? Another challenge has been to develop assessment tools that provide some detail about what students know of the various NOS subdomains such as those indicated in Table 61.7.

Therefore, some effort must be expended to develop valid and reliable NOS assessment instruments with useful and robust subscales to help determine what students understand about the nature of science and make sure that such items are included on all end-of-course examinations. Completing both of these tasks will encourage educators to include NOS in instruction, while the results of these assessments will permit educators and researchers to visualize what specific elements of NOS are being communicated effectively in schools.

61.10 Science Teacher Preparation and the Nature of Science

Another force that has potential to unite the states with respect to science teaching relates to preparation of science teachers. Many states have adopted the teacher education standards associated with one of the national accreditation organizations (such as the National Council for the Accreditation of Teacher Education or NCATE), a nongovernmental group. Therefore, by default and design, the teacher education programs governed by NCATE have common elements because of the guidelines imposed on them by these accreditation boards.

This issue becomes somewhat complicated because NCATE refers instructions that prepare teachers to the science content standards developed by the National Science Teachers Association (NSTA). The NCATE database shows that there is at least one academic institution within each state in the United States accredited by NCATE. So, for those science teacher education programs that use NCATE/NSTA, the 2003 standards are quite detailed with respect to the nature of science.

Strand 1 of the NSTA Standards (NSTA 2003) (science content) requires that teachers have implicit knowledge of nature of science under the subheading "concepts and principles" and perhaps "unifying concepts." Explicit knowledge is required under Standard 2 (nature of science), which includes both history of science and nature of science. The rationales provided for NOS inclusion are strong and include many of the NOS elements mentioned frequently by science educators including issues such as tentativeness, empiricism, subjectivity, creativity, the use of inference, the lack of a step-by-step scientific method, and the fact that science is embedded in culture. As well, we find recommendations for teaching NOS in an explicit fashion and the use of history to augment NOS lessons.

Beyond this general reference to NOS and NCATE/NSTA, the nature of science is specifically referenced in the competencies only for the states of Texas, Oklahoma, Florida, Missouri, and Massachusetts. As an example, the *Preparation Manual for the Texas Examinations of Educator Standards in* Domain I for Life Science states:

> The science teacher understands the process of scientific inquiry and its role in science instruction. The science teacher understands the history and nature of science. The science teacher understands how science affects the daily lives of students and how science interacts with and influences personal and societal decisions. The science teacher knows unifying concepts and processes that are common to all sciences. (Texas Examination of Educator Standards 2006, p. 6)

Competency 2 further describes what the beginning teacher should know about nature of science, the process of scientific inquiry, and the unifying concepts that are common to all sciences.

The required competencies in the biological sciences for Oklahoma list two areas with explicit reference to nature of science. Competency 2 requires that students "understand the nature of science including the historical and contemporary contexts of biological study" (p. 2–2). Competency 3 is to "understand the process of scientific inquiry and the role of observation, experimentation, and communication in explaining natural phenomena" (Oklahoma Subject Area Tests – Study Guide, p. 2–3). Florida (Florida Department of Education 2011) provides the most comprehensive inclusion of nature of science within the teacher licensure requirements in listing nature of science within all science disciplines including biology, physics, chemistry, and Earth-space science.

The Missouri Department of Elementary and Secondary Education Certification Requirements for Secondary Education (2009) require two semester hours of study in the history/philosophy of science and technology for all secondary science certifications. Under the regulations for educator licensure and preparation approval (603 CMR 7.00), Massachusetts (2012) lists subject matter knowledge requirements for teacher licensure that include methods of research in the sciences, history and philosophy of science, and principles and procedures of scientific inquiry (which many now include as part of the nature of science).

The licensure requirements for the majority of other states demand that a prospective teacher have a degree in the content area plus passing the Praxis II test.

Based on the *Biology: Content Knowledge* informational guide available from the developer of the test, the Educational Testing Service (ETS), we find approximately 12–22 multiple-choice questions out of the total 150 questions that relate specifically to NOS knowledge. These are all listed under the heading *Basic Principles of Science.* The nature of science questions relate to processes involved in scientific inquiry such as making observations, formulating and testing hypotheses, identifying experimental variables and controls, drawing scientific conclusions, and using scientific sources and communicating findings appropriately. Questions also relate to distinguishing differences among facts, hypotheses, theories, and laws; the testable nature of hypotheses; formulation of theories based on accumulated data; and the durability of laws. Finally, questions are also included that deal with the idea that scientific ideas change over time. These explicit questions about the nature of science comprise approximately 8–15 % of the Praxis II content knowledge test for biology, for example.

This is encouraging; it is clear that those thinking about science teacher preparation have come to value the nature of science, and there is some expectation that teachers who complete accredited programs would have some basic knowledge of NOS. Of course, there is no way of knowing if these teachers value and include NOS content in their classes nor do we know if these teachers preparation programs include a discussion of curriculum strategies for teaching the nature of science.

61.11 US Textbooks and Curriculum Innovations to Support NOS Instruction

One way that nature of science could become a more visible and integral part of the science curriculum is through its focused inclusion in science textbooks. If texts were to feature strong NOS elements – particularly if NOS is included throughout the book – there is a good chance that teachers and students would give more attention to this important topic.

However, in the highly competitive world of textbook publishing in the United States and the long-standing principle of permitting most schools to choose which science books to purchase, all textbooks authors will have to focus more clearly on the nature of science. This is more likely now given the widespread adoption of the *Next Generation Science Standards* and their reasonable focus on the nature of science. The challenge is not just to ensure that science textbooks include an accurate treatment of the nature of science linked to the traditional science content, but such books must integrate NOS throughout the text in a robust fashion.

The hope is that new texts will avoid the current tradition in which whatever NOS content included is relegated to the opening chapter with almost no additional NOS content woven into the subsequent chapters that feature standard science content. This is unfortunate, because many teachers likely move quickly through or skip that first chapter and therefore miss opportunities to share NOS content with students. An additional challenge is for teachers to have access to curriculum models to support engaging instruction in the nature of science. As we will see, although some models have been developed, almost none have entered common use.

61.11.1 Curriculum Innovations and the Nature of Science

Even though explicit and wide-ranging NOS lessons are all absent from current US textbooks, there have been a few important curriculum projects designed to support NOS instruction. The first example of a project targeting NOS instruction draws on the history of science and a set of ancillary study units that apply the case approach. The next two come as a direct result of the US government funding designed to reinvigorate and redirect science and mathematics education through new curriculum models following the launch of Sputnik in the late 1950s. These examples include a classic "alphabet soup" curriculum project called *Science – A Process Approach*; a textbook, *Project Physics*, with multiple NOS inclusions; and several media-centered approaches. There are other NOS examples found in a review of the history of curriculum development in the United States, but sadly none made long-lasting impacts on the inclusion of NOS in the typical science classroom. However, all of these stand as important testaments to the potential a NOS-focused science curriculum and should be studied carefully by those wishing to reestablish the nature of science in science instruction.

61.11.2 The Case History Approach: Conant and Klopfer

A focus on NOS in these curriculum innovations was offered in the previous decade by J.B. Conant an influential scientist, government official, and president of Harvard who stated "…it is my contention that science can best be understood by laymen through close study of a few relatively simple case histories…" (Conant 1947, p. 1). With this simple statement, the use of history as a dominant approach to NOS instruction was born.

Conant's suggestion for the use of history of science in science instruction resulted in what is the most noteworthy example of the case approach, *The Harvard Case Studies in Experimental Science,* which grew out of a general education course beginning at Harvard in 1948 and ultimately published in two volumes (Conant and Nash 1957). The seven cases focused on issues such as Robert Boyle and pneumatics, phlogiston theory, temperature and heat, atomic molecular theory, plants, spontaneous generation, and the historical development of the concept of electric charge.

Later, Conant's student and later fellow Harvard professor, Leo Klopfer along with Cooley (1963), adapted the case study approach for use in high schools with *the History of Science Cases (HOSC)*. Each of these units included the exploration of a major scientific idea through the examination of excerpts of historical documents and experimentation carried out either by students themselves or as a demonstration by the teacher (Lind 1979). The nine titles proposed or developed for HOSC were each represented by individual guides for teachers and their students. The units included exploration of cells, the chemistry of carbon dioxide, Fraunhofer lines, electricity and life (with the intriguing title *Frogs and Batteries*), the discovery of halogen elements, air pressure, plant reproduction, atomic theory, and the speed of light.

The overarching goals for HOSC were to show students the methods used by scientists; the means by which science advances and the conditions under which it flourishes; the personalities and human qualities of science; the interplay of social, economic, technological, and psychological factors with the progress of science and the importance to science of accurate and accessible records; constantly improved instruments; and free communication between scientists (Klopfer 1964).

61.11.3 S-APA: Science: A Process Approach

This project was developed starting in 1962 by the AAAS Commission on Science Education with funding from the National Science Foundation based on the learning theories of psychologist Robert Gagne. The basic premise of S-APA was that the "first and central purpose of science education is to awaken in the child, whether or not he will become a professional scientists, a sense of the joy, the excitement, and the intellectual power of science" (AAAS 1967, p. 1). The basic notion was to give students a variety of hands-on experiences based on a hierarchy of skills (called process skills) that scientists were seen to use regularly.

The processes that the students experienced included observation, classifying, using numbers, measuring, using space/time relationships, communicating, predicting, and inferring (called the basic processes for the primary grades). These were joined by integrated process for upper grade students and included defining operationally, forming a hypothesis, interpreting data, controlling variables, and experimenting.

It should be clear that a number of important NOS ideas were contained among the processes even though S-APA was not designed expressly to communicate such goals. Unfortunately, S-APA like so many of these curriculum projects was never widely used. It quickly faded from the scene because of its uniqueness, its lack of focus on science content, and its decontextualized nature (Finley 1983). However, many of the individual lessons provide wonderful lesson opportunities for teachers today who want a hands-on approach to the nature of science.

61.11.4 Project Physics: NOS in a Textbook Setting

One of the most important text-based projects to feature NOS was *Project Physics* (also called *Harvard Project Physics*) authored by Gerald Holton, F. James

Rutherford, and Fletcher Watson. This book was remarkable in its desire to merge the traditional content of physics with the human side of science. In the introduction to the 1981 edition, the authors write that one of their goals was for students to see "physics as the wonderfully many-sided human activity that it really is. This meant presenting the subject in historical and culture perspective…" (p. iii). The book meets this challenge on almost every page by prominently discussing the people who contributed to modern physics.

As an example, consider the prologue which begins "It is January 1934 in the city of Paris. A husband and wife are at work in a university laboratory. They are exposing a piece of ordinary aluminum to a stream of tiny changed bits of matter called alpha particles" (Holton et al. 1981, p. 1). It is impossible to find another science text that so deliberately shares the human side of science with students in such an explicit fashion. It the pages of *Project Physics*, readers could encounter all of the greats and near-greats of physics while learning the traditional science content.

With both Conant's case study approach and the humanistic physics of Holton, Rutherford, and Watson, we see innovative approaches to the inclusion of nature of science content in science curriculum. Sadly, there have been very few other such products, and even these were only marginally successful. Project Physics had a much longer life; it was produced in several editions, and by far more teachers and students than the case study materials or *S-APA*, but in the end, neither approach can be found in use today.

61.11.5 Using Media to Teach the Nature of Science

There have been some excellent ancillary materials produced such as the *Mechanical Universe Project* created and hosted by David Goodstein of the California Institute of Technology in 1985 and *Mindworks* in 1994 by Barbara Becker (Becker et al. 1995). Both of these initiatives produced high-quality video reenactments of important scientists and their discoveries. The good news is that *Mechanical Universe* is available on line for streaming by teachers who would like to use the reenactments to enliven their presentations of science content and teach some important NOS lessons at the same time.

In fairness, many former curriculum projects and current texts do include some discussion of NOS, typically in the opening chapter, and often feature the names and dates of the most famous scientists, typically in side bar material. Unfortunately, NOS in this fashion is too easy to ignore by teachers and students. The sad reality is that in spite of a number of notable innovations including those mentioned here, the US science curriculum today does not look much different than it did before the widespread interest in and rationales for the inclusion of the nature of science.

61.12 Conclusion

The United States is a unique environment for education with its decentralized educational bureaucracy, a multitude of special interest groups involved in policymaking, free-market choice of textbooks, and individual state control over the curriculum and end-of-course (or exit) assessments. However, this review provides some reasons to be encouraged. We have seen the development of some interesting curriculum models to support NOS instruction, and there is increasing and widespread interest on the part of the science education community that NOS is an important learning goal. In addition, science educators have provided strong rationales for the inclusion of NOS and have defined a set of NOS sub-domains appropriate for use in school settings. *The Next Generation Science Standards* feature most of the recommended elements of NOS in a prominent fashion using a spiral curriculum approach to ensure that NOS is included each year. Perhaps the states will respond to these new standards by requiring that preservice teachers have significant experience with the nature of science. This suggestion for improvement cannot be overstated. Those who teach science certainly will have learned much science content while earning their degrees, but the same claim may not be made regarding teachers' understanding of how science functions. As a case in point, only science teachers repeat the inaccurate notion that there is a scientific method; scientists know better. However, science teachers learned this faulty idea in the pages of the science textbooks since they learned very little about the structure and processes of science while digesting the diet of "final form" science in their prior school and university experiences. Perhaps if those learning science were permitted to look "behind the curtain" and gain an understanding of the nature of science, those who become teachers could carry those lessons into their classrooms.

On the other hand, there are reasons to be concerned. Currently, NOS is not a topic of any prominence in most US science textbooks and is certainly not included in texts in a systematic and explicit fashion. It is unclear what new teachers need to know and be able to do with respect to NOS leading to concern that they may simply ignore this content. Only with strong curriculum models aligned to the NOS content in the *NGSS* and shared examinations that include a strong NOS component will the promise offered by robust inclusion of NOS become a reality.

The inescapable conclusion is that the history and philosophy of science must be a strong part of science teacher preparation, must be included in standards in a clear and robust fashion, must be featured in an engaging fashion in textbooks, and must be assessed on science exit examinations. With these challenges in mind, there is hope that the nature of science will take its place along with traditional science content as a vital part of the science learning experience for the next generation of US science learners.

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Chapter 62
The History and Philosophy of Science in Science Curricula and Teacher Education in Canada

Don Metz

62.1 Introduction

In Canada, the contributions to the field of history and philosophy of science (HPS) and the role and influence of HPS and science education have a rather recent, but significant, history. In the last few decades, we find influential philosophers such as Mario Bunge, Ian Hacking, and Paul Thagard; noted historians of science such as Stillman Drake; and influential science educators like Derek Hodson, Jacques Désautels, Glen Aikenhead, Arthur Stinner, Stephen Norris, and Kieran Egan (and many more, too numerous to mention) providing a diverse and extensive collection of books, essays, journals, lectures, conference keynotes, and graduate students in the field of HPS.

Indeed, many of these Canadian academics have enjoyed a wide range of international success and recognition. Mario Bunge, still active in his 90s, alone has contributed over 80 books and 400 journal articles in his tenure including his oft-referenced eight-volume *Treatise on Basic Philosophy* (1974–1989). Ian Hacking, well known for his defense of entity realism, wrote the introduction to Feyerabend's (1975) "*Against Method*," and Stillman Drake is universally considered to be the authority on Galileo, publishing over 130 books and articles on the great master (Buchwald and Swerdlow 1993, p. 663). More recently, Paul Thagard has emerged as a leader in the field of philosophy and cognitive science (Thagard 2010[1]). In the field of science education, Derek Hodson gave us the influential "Towards a Philosophically More Valid Science Curriculum" (Hodson 1988) and recently published *Towards Scientific Literacy: A Teachers' Guide to the History, Philosophy and Sociology of Science* (Hodson 2008). Nadeau and Désautels (1984) advanced an

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[1] Note that Thagard (2010) is just the most recent of many books in philosophy and cognitive science by Paul Thagard.

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epistemological perspective, and Glen Aikenhead provided an often-used research instrument on the Views on Science, Technology, and Science (Aikenhead and Ryan 1992) and has worked extensively in the last number of years arguing for a cultural component in science education. Arthur Stinner's Large Context Problems are widespread and cited by many (Stinner 1995), and Stinner's dramatizations are well known at the conferences of the International History and Philosophy of Science and Science Teaching organization. Additionally, in terms of scientific literacy and its connections to literacy, we find significant contributions from Stephen Norris (Norris et al. 2005), and in terms of narrative and story structuring, Kieran Egan has argued that language and reality develop with a constant interaction using intellectual tools of metaphor, imagery, and binary structuring (Polito 2005).

It is always somewhat risky to highlight so few examples of HPS in your own country when many more contributions to conferences (three of the ten IHPST conferences have been hosted in Canada), journals (editors like Ian Winchester), books (Roth and Desautels 2002), countless journal articles, and contributions in the field of curriculum can be found. However, to the reader, I provide these brief references to provide a context in which I can lay the foundations of a review of HPS in science curricula and teacher education in Canada.

Education in the Canadian political system is a provincial responsibility. Given a geographically expansive country, a diversity of cultures, and ten provinces and three territories, the role of history and philosophy of science (HPS) in science education varies considerably across the nation. In this chapter, I will explore a wide range of aspects of HPS and the teaching of science in Canada. Some of these aspects will include the evolution of ideas surrounding Science, Technology, and Society (STS) and a move towards scientific literacy and "Science for All." These features include the historical underpinnings of the history and philosophy of science and science curricula, the influence HPS has had on national and provincial curriculum from the process/product debates of the 1960s to the national conversations surrounding the 1993 Victoria Declaration (CMEC 1999), and the 1997 Pan-Canadian protocol (CMEC 1997). Additionally, I will address the inclusion of HPS in teacher education programs (including some best practices) and some recent developments. Finally, some time will be taken to examine the status of local indigenous knowledge, specifically its integration in science curriculum in the province of Saskatchewan.

62.2 Historical Perspectives

An early reference to the inclusion of HPS in curriculum in Canada can be found in a memorandum that was signed in 1962 by many prominent mathematicians in the United States and Canada.[2] Among other things the memorandum called for as a fundamental principle a genetic method:

> **Genetic method**. "It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in

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[2] On the Mathematics Curriculum of the High School, The Mathematics Teacher of March 1962, American Mathematical Monthly of March 1962

> then ascent state." wrote James Clerk Maxwell. There were some inspired teachers, such as Ernst Mach, who in order to explain an idea referred to its genesis and retraced the historical formation of the idea. This may suggest a general principle: The best way to guide the mental development of the individual is to let him retrace the mental development of its great lines, of course, and not the thousand errors of detail. (Ahlfors et al. 1962, p. 426)

Two Canadians signed the memorandum, the prominent geometer H. S. M. Coxeter, from the University of Toronto, and a relatively new Canadian Alexander Wittenberg, from Laval University. Coxeter was very active in the Upper Canada Branch of the Canadian Society for the History and Philosophy of Science for many years. As well, the Canadian Mathematical Bulletin reported in 1963 that Wittenberg was appointed as a professor of mathematics at York University in Toronto. At this time, York was in the process of developing courses to relate mathematics to the humanities and social sciences as well as the natural sciences. Wittenberg was to initiate this venture by developing a first year course in mathematics and philosophy. Hayo Siemsen (2011), tracing the influences of Ernest Mach in science education, notes the strong connections of Wittenberg to such notable professors as Pólya and Nevanlinna, and he argues convincingly about the influence that Mach had on science education (quite an obvious influence on Wittenberg it seems from the inclusion of the genetic method in the aforementioned memorandum). Siemens further suggests that is was Wittenberg who provided Freudenthal with the initial ideas leading to the PISA study (see Wittenberg 1965, 1968; Siemsen and Siemsen 2008, 2009). Wittenberg could then be considered to be an early pioneer in Canada promoting the inclusion of HPS. However, Wittenberg unfortunately died at an early age and published very little. The reality is that he had very little influence and is essentially unknown in the country because of his early demise. The genetic method, a historical approach to knowledge, had no influence in curriculum developments and remained for the most part and academic argument.

In most developed countries, the science curriculum, often referred to as "school science" (Duschl 1994), generally provides a wide breadth of coverage intended to prepare students for postsecondary science courses acting as a "pipeline" to future studies (Millar and Osborne 1998). Glen Aikenhead (2003), tracing the origins of school science in the Western tradition, notes that traditional science curriculum "assumes that 'science' in 'school science' has the same meaning as it has in, for example, 'the American Association for the Advancement of Science'" (p. 3). That is, the science curriculum is essentially a nineteenth-century curriculum in scope and intent.

The Canadian curriculum for the first half of the twentieth century generally followed this model with a great emphasis on the training of scientists and engineers in the 1960s and 1970s fueled by international competition and the space race. In reflection, Rutledge (1973) notes "The concern was also expressed that too little emphasis was being given to the philosophy and processes of science and that meaningful laboratory work was not an important part of most school science" (p. 600). However, emerging from these concerns, a large number of curriculum resources were produced that mostly focused on the processes of science. Many of these resources such as Science: A Process Approach (AAAS 1967), Science Curriculum Improvement Study (SCIS 1972), Elementary Science Study (EDC 1969), Physical Science Study Committee (PSSC 1960), Chemical Education

Material Study (CEMS 1960), Biological Sciences Curriculum Study (BSCS 2006), Earth Science Curriculum Project (Heller 1964), and Introductory Physical Science Program (ESI) found their way into Canadian science curricula. As elsewhere, the need for scientists was considered essential, and although it was generally accepted that all students needed to be "scientific literate," this literacy was oriented towards investigations, observation, learning of abstract concepts, and the acquisition of knowledge as though the student had discovered it. In general, weaknesses identified in these approaches were a failure to meet the needs of the general student population, readability levels were usually above the grade level, and most experiments and investigations were close ended rather than open ended (Baptiste and Turner 1972). Others argued that "there was no basis in school science on which to develop a critique of the role science plays in society or an appreciation of its strengths and limitations" (Fensham 1973, cited from Fensham 1997, Reconsidering Science Learning, p. 22).

With the advent of curricula that focused on the preparation of scientists, criticism began to emerge at that time that questioned why the only students worthy of curricular attention were those who might become professionals. Questions concerning "science for whom?", the balance of content and process, the relevance of the curriculum, and the emphasis on the transmission model of instruction were beginning to be asked by many educators and scientists themselves.

As an effort to address the relevance of science curriculum, the early development of a humanistic alternative to school science could be found in Science, Technology, and Society (STS) programs formally initiated in the late 1960s, in the United States, United Kingdom, Australia, and the Netherlands (Aikenhead 2003; Solomon and Aikenhead 1994). Aikenhead argued that "These university academic programs responded to perceived crises in responsibility related to, for instance, nuclear arms, nuclear energy, many types of environmental degradation, population explosion, and emerging biotechnologies. Thus, social responsibility for both scientist and citizen formed one of the major conceptions on a humanistic perspective in school science" (p. 8).

The dichotomy of purposes of science education, that is, science for future scientists versus a more humanistic approach for scientific literacy, helped fuel debates about the purposes of science education in the country. For example, the introduction of an STS orientation of high school science courses was not well received by university faculty. In some provinces, STS science courses were not approved for university entrance.

An important step in examining the various viewpoints in science education was initiated in the 1980s by the Science Council of Canada (SCC). The SCC was created by the federal government in 1966 to advise the government on science and technology policy (Millin and Steed 2012). The SCC members were broadly representative of the Canadian scientific community, in both the academic and private sectors. Consisting of a panel of 30 experts from the natural and social sciences and from business and finance, they produced many published works which were qualified by the council for reliability and methodology. In some cases, these reports provided recommended actions to governments or other institutions. However, the reports were most often intended to create a climate for policy debate rather supporting specific guidelines for government action.

In order to foster dialogue in science education, the SCC undertook a series of four discussion papers for a study of Canadian science education in the early 1980s. As noted by Hugh Munby (1982), one of the objectives was "to stimulate active deliberation concerning future options for science education," suggesting that the Science Council had no collective view on a direction for science education in Canada and in order to develop such a view, it was soliciting a variety of viewpoints.

The position papers were "A Canadian Context for Science Education" by James Page (1980) who argued that science education could contribute to "improved national awareness." A second paper by Glen Aikenhead (1980), "Science in Social Issues: Implications for Teaching," supported the view that science should be taught such that students learn about social and political issues. A third paper, "An Engineer's View of Science Education," by Donald George (1981) advocated for the equal treatment of the engineer's intellectual processes, and the final paper of the series, "What is Scientific Thinking?," by Hugh Munby (1982) examined what it meant to think critically and scientifically. The SCC's work culminated with an extension research program which included examination of the science curriculum guidelines in every province and territory, an analysis of common textbooks, survey of teachers and students, and case studies of science teaching across the country. Additionally, 11 conferences attended by ministry officials, school board members, teachers, students, and representatives from university, labor, and industry helped produce a consensus which endorsed a position of "Science for All" (SCC 1984).

The SCC report 36, "Science for Every Student: Educating Canadians for Tomorrow's World," established a goal of scientific literacy for all with four broad aims:

To encourage full participation in a technological society
To enable further study in science and technology
To facilitate entry to the world of work
To promote intellectual and moral development of individuals

Among the 47 recommendations, we find a recommendation to incorporate a science-technology-society emphasis in science courses at all levels and a recommendation to "ensure that courses at all levels present a valid representation of the nature of science and scientific activity through the judicious use of examples from the history of science" (p. 48).

While these recommendations perhaps fostered some debate, there is little evidence that they influenced provincial or national curriculum at the time (except perhaps by the individuals locally). Arguably, it was the slow process of curriculum development and not the debate that was most influential. Curriculum development in Canada is usually marked by major overhauls in 20-year (approximately) intervals. At this time, any significant changes would have to wait.

Around the same time as the SCC report, The National Science Teachers' Association adopted Science, Technology, and Society (STS) as its official position for science education (Yager 1993, p. 145). Many other countries also developed resources to address teaching of STS. For example, in the United Kingdom, we find Science in a Social Context (Solomon 1983), and in Canada, SciencePlus (ASCP 1988) was developed in Atlantic Canada and used across various provinces. As ideas around STS, STSE (adding the Environment), and socioscientific issues began to evolve, the Canadian context, especially in terms of the intended curriculum, began to advance towards a more national viewpoint. Aikenhead (2000), following the work of Rosenthal (1989) and Ziman (1984), illustrates two types of social issues in STS science that began to envelope the views of most science educators:

1. Social issues *external* to the scientific community ("science and society" topics, e.g., energy conservation, population growth, or pollution)
2. Social aspects of science – issues *internal* to the scientific community (the sociology, epistemology, and history of science, e.g., the cold fusion controversy, the nature of scientific theories, or how the concept of gravity was invented)

Aikenhead also noted that these views would be flexible enough to embrace the different goals and content found the curricula across different provinces. Ultimately, these dual issues began served as a major influence in the development of the Pan-Canadian Framework's STSE emphasis.

Today, many Canadian educators continue work on these STSE issues, in both external[3] and internal aspects of STS science.[4]

62.3 Pan-Canadian Science Framework

Generally, provincial curricula in Canada have been developed through the years independently by each province with varying degrees of cooperation. No national curriculum existed in any form. As a result, a considerable amount of disparity and unnecessary duplication of effort existed among the provinces. Moreover, families moving from one part of the country to another were often caught in a curriculum mismatch with children repeating some content while completely missing other topics.

Recognizing that with increased mobility of Canadians, a more coordinated effort would help harmonize the curriculum nationally and provide some economies of scale, the Provincial Ministers of Education (Canadian Ministers of Education of Canada (CMEC)) agreed on the Victoria Declaration in 1993 identifying education as lifelong learning and highlighting the need for national curriculum compatibility (Milford et al. 2010). The CMEC established the Pan-Canadian Science Project as the first national curricular effort, culminating with the development of the *Common Framework of Science Learning Outcomes* (CMEC 1997). The framework was intended as a guide for provinces to develop their own curriculum based on the framework, giving some degree of

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[3] For example, see Yore (2011), Pedretti (1997), Pedretti et al. (2008), Pedretti and Hodson (1995), Sammel and Zandvliet (2003), and Bencze (2010).

[4] For example, see Norris and Phillips (2003), Stinner (2003), and Klassen (2006).

commonality between the provincial jurisdictions. In reference to the development of the framework, Aikenhead (2000) writes:

> In keeping with Canadian culture, the *Common Framework of Science Learning Outcomes* (the *Framework*) evolved through negotiation and compromise among provincial bureaucrats, advised by interested parties (stakeholders) in each province. This political process, however, did not meet the standards of curriculum policy development held by the Canadian science education academic community. (p. 51)

Aikenhead, who was instrumental in the previous debates more than a decade earlier on the nature of science education promoted by the Science Council of Canada (SCC), contrasted the processes followed by the CMEC and SCC. He noted that the SCC conducted educational studies "with the highest of scholarly standards," while the CMEC allowed the provincial civil servants, many with little expertise or research knowledge in field of study they were addressing, to complete the framework. Many science educators, originally recruited as consultants intended to provide input at the national level, were relieved of their responsibilities when some provinces did not want to fund equal participation. In other words, participation was reduced to the lowest common denominator.

However, as Aikenhead also noted, some of the conclusions of the SCC science education study in the early 1980s did find their way into the CMEC's bureaucratic negotiations and development of the framework. Additionally, other international documents such as the US National Research Council's *Standards* (NRC 1996) and Project 2061 (AAAS 1989) were significant influences. By the late 1990s the framework, with a major emphasis on STSE goals, became a set of guidelines for science curricula across the country.

A critique of the framework, which in the author's opinion suffers greatly as compendium of fragmented outcomes, is beyond the scope of this paper. However, within the framework, many outcomes with respect to the history and nature of science begin to emerge in Canadian science education for the first time and merit mention here. The framework takes the position that the promotion of students' scientific literacy requires students' understanding of HPS and the nature of science (NOS) for rational and scientific decision making in an everyday context.

As a vision for scientific literacy, four foundation statements were established for this framework:

1. Science, Technology, Society, and the Environment (STSE)
2. Skills
3. Knowledge
4. Attitudes

It is within the STSE foundation that we find explicit mention of the nature of science (although it is always coupled with technology, i.e., "the nature of science and technology"). The STSE foundation focuses on three major dimensions: the nature of science and technology, the relationships between science and technology, and the social and environmental contexts of science and technology. Table 62.1 highlights the HPS and NOS attributes that are found in the description of the STSE foundation.

Table 62.1 HPS and NOS attributes

Nature of science and technology
Science is a human and social activity with unique characteristics and a long history that has involved many men and women from many societies. Science is also a way of learning about the universe based on curiosity, creativity, imagination, intuition, exploration, observation, replication of experiments, interpretation of evidence, and debate over the evidence and its interpretations. Scientific activity provides a conceptual and theoretical base that is used in predicting, interpreting, and explaining natural and human-made phenomena. Many historians, sociologists, and philosophers of science argue that there is no set procedure for conducting a scientific investigation. Rather, they see science as driven by a combination of theories, knowledge, experimentation, and processes anchored in the physical world. Theories of science are continually being tested, modified, and improved as new knowledge and theories supersede existing ones. Scientific debate on new observations and hypotheses that challenge accepted knowledge involves many participants with diverse backgrounds. This highly complex interplay, which has occurred throughout history, is fuelled by theoretical discussions, experimentation, social, cultural, economic, and political influences, personal biases, and the need for peer recognition and acceptance
While it is true that some of our understanding of the world is the result of revolutionary scientific developments, much of our understanding of the world results from a steady and gradual accumulation of knowledge
Social and environmental contexts of science and technology
The history of science highlights the nature of the scientific enterprise. Above all, the historical context serves as a reminder of the ways in which cultural and intellectual traditions have influenced the questions and methodologies of science and how science in turn has influenced the wider world of ideas

The framework itself is organized into general learning outcomes (GLOs), which are established for each foundation. General learning outcomes are broad statements of what students are expected to learn and be able to do. Table 62.2 shows the GLOs for the STSE foundation, many of which address HPS, STSE, and NOS outcomes.

In turn, the GLOs are delineated into several specific learning outcomes (SLOs). The GLOs and SLOs are then linked to specific learning outcomes in the knowledge foundation (the SLOs are not shown here). Each GLO in Table 62.2 has a similar path that can be traced to knowledge outcomes. Sometimes the GLO is represented in more than one outcome, and sometimes it may not be represented at all. One should note that the curriculum remains organized in the traditional way in terms of knowledge outcomes. While the inclusion of the nature of science outcomes should be seen as encouraging progress, the outcomes are scattered across a wide range of knowledge outcomes. In conclusion, we can say that in terms of promoting HPS in the science curriculum, we see for the first time in Canada a set of general and specific learning outcomes. While this is a very positive development, these outcomes are fragmented and dispersed without any clear connections to any overall perspective on the nature of science. In other words, we now have HPS and NOS outcomes, but there is no coherent approach to teaching of the nature of science.

Table 62.2 General learning outcomes (GLO) for the STSE foundation

It is expected that students will…	
109	Describe various processes used in science and technology that enable us to understand natural phenomena and develop technological solution
110	Describe the development of science and technology over time
111	Explain how science and technology interact with and advance one another
112	Illustrate how the needs of individuals, society, and the environment influence and are influenced by scientific and technological endeavors
113	Analyze social issues related to the applications and limitations of science and technology, and explain decisions in terms of advantages and disadvantages for sustainability, considering a few perspectives
114	Describe and explain disciplinary and interdisciplinary processes used to enable us to understand natural phenomena and develop technological solutions
115	Distinguish between science and technology in terms of their respective goals, products, and values, and describe the development of scientific theories and technologies over time
116	Analyze and explain how science and technology interact with and advance one another
117	Analyze how individuals, society, and the environment are interdependent with scientific and technological endeavors
118	Evaluate social issues related to the applications and limitations of science and technology, and explain decisions in terms of advantages and disadvantages for sustainability, considering a variety of perspectives

62.4 HPS Outcomes in Provincial Curriculum: Ontario

We also must remember at this point that the framework is intended as a guideline and each province may (or may not) adapt the curriculum in their own way. Indeed, this is exactly what has happened. For example, the Ontario (Canada's largest province) curriculum organizes expectations for the grades 11 and 12 science courses in five strands that are intended to "where possible" align with the topics set out in the *Pan-Canadian Common Framework of Science Learning* Outcome (CMEC 1997). Table 62.3 shows how an HPS outcome can be traced to the Ontario provincial curriculum implementation from the vision present in the framework to the implementation aligned with specific knowledge outcomes. The GLO (general learning outcome) (GLO – 114), "Describe and explain disciplinary and interdisciplinary processes used to enable us to understand natural phenomena and develop technological solutions," has nine specific learning outcomes in the framework

Table 62.3 Tracing an HPS outcome to provincial curriculum

Vision

Science is a human and social activity with unique characteristics and a long history that has involved many men and women from many societies

General learning outcome (GLO – 114)

Describe and explain disciplinary and interdisciplinary processes used to enable us to understand natural phenomena and develop technological solutions

Specific Learning Outcome (SLO – 114.x)

114-1

Explain how a paradigm shift can change scientific worldviews

114-2

Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge

114-3

Evaluate the role of continued testing in the development and improvement of technologies

114-4

Identify various constraints that result in trade-offs during the development and improvement of technologies

114-5

Describe the importance of peer review in the development of scientific knowledge

114-6

Relate personal activities and various scientific and technological endeavors to specific science disciplines and interdisciplinary studies

114-7

Compare processes used in science with those used in technology

114-8

Describe the usefulness of scientific nomenclature systems

114-9

Explain the importance of communicating the results of a scientific or technological endeavor, using appropriate language and conventions

Life science	**Chemistry**	**Physics**	**Earth science**
114-2	*114-2*	*114-2*	*114-2*
Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge (e.g., explain how the cloning of a sheep in 1997 affected the scientific theory of differentiation)	Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge (e.g., explain how bonding theory can help one understand certain colligative properties)	Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge (e.g., explain the role of evidence and theories in the concept of fields)	Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge (e.g., describe the historical development of theories to explain the origin of the universe)

document as shown in Table 62.3. I show how one of these, 114-2, “explain the roles of evidence, theories, and paradigms in the development of scientific knowledge,” can be found in a knowledge outcome for each science course, biology, chemistry, earth science, and physics, at the secondary level (from the framework). Table 62.4

Table 62.4 HPS at the provincial level (GLO 114-2)

Life Sciences	The Ontario expectation is virtually exactly the same as the framework
Earth Science	The Ontario intent is the same but the wording is different, i.e., "describe origin and evolution of the Earth and other objects in the solar system"
Chemistry	There is no corresponding outcome in Ontario
Physics	The Ontario intent is the same but specific reference to models and evidential examples are provided

describes how the outcome appears in the Ontario curriculum. It is possible, although somewhat challenging and time-consuming, to trace each GLO and SLO to a knowledge outcome.

Thus, we can see that for the most part the nature of science outcomes as described in the framework is making its way into the provincial curriculum documents. Although some of the outcomes may be omitted, we can find many outcomes that have actually been enhanced, and even new outcomes emerge as they may relate to local interests. For example, our physics outcome becomes in Ontario:

> explain how the concept of a field developed into a general scientific model, and describe how it affected scientific thinking (e.g., explain how field theory helped scientists understand, on a macro scale, the motion of celestial bodies and, on a micro scale, the motion of particles in electromagnetic fields). (Ontario 2000, p. 108)

And in terms of local interest, we can find outcomes such as:

> describe advances in Canadian research on atomic and molecular theory (e.g., the work of Richard Bader at McMaster University in developing electron-density maps for small molecules; the work of R.J. LeRoy at the University of Waterloo in developing the mathematical technique for determining the radius of molecules called the LeRoy Radius). (Ontario 2000, p. 65)

We must see the adoption of these types of outcomes as a positive step in promoting an understanding of HPS in science curriculum and as a step towards achieving many of the claims of the HPS community of the benefits of using an HPS approach in science education (Matthews 1994; Winchester 1989). However, the inclusion of the HPS outcomes still remains mostly ad hoc and fragmented without any internal consistency in the science programs. Such consistency can be found in independent courses in philosophy that are offered through such programs as the International Baccalaureates (IB) and as stand-alone courses such as teaching philosophy in high school. These courses, worthwhile and generally taught with some expertise, are offered as electives and usually found as "gifted and talented" offerings in some jurisdictions.

This emergence of a coherent curriculum in philosophy (albeit more general), the growing acceptance of philosophy as a teaching major or minor in more provincial jurisdictions, and the organization of teachers associations such as the Ontario Philosophy Teacher's Association should be seen as positive force in the future for the continued development of the inclusion of HPS in curriculum in general and in science education specifically. Arguably, Canadians who support an HPS perspective are pleased with the progress, albeit flawed in many ways. However, we should take our pleasure with some caution.

62.5 HPS Outcomes in Provincial Curriculum: Saskatchewan

Contrasting the Ontario use of the Pan-Canadian Framework is the recent development of the Saskatchewan science curriculum. The province of Saskatchewan is in Western Canada and has a population of just over one million persons with approximately 16 % Indigenous and Métis people. The vision for science education in the province is stated in the Saskatchewan Learning Science 9 Curriculum Guide:

> The aim of K-12 science education is to enable all Saskatchewan students to develop scientific literacy. Scientific literacy today embraces Euro-Canadian and Indigenous heritages, both of which have developed an empirical and rational knowledge of nature. A Euro-Canadian way of knowing about the natural and constructed world is called science, while First Nations and Métis ways of knowing nature are found within the broader category of Indigenous knowledge (Hounjet et al. 2011). (Sask Science 9, p. 5)

The Saskatchewan curriculum delineates the foundations of the Pan-Canadian Framework from a cultural perspective. For example, traditional and local knowledge is included alongside of life, physical, earth, and space science knowledge. Scientific knowledge is represented as a set of understandings, interpretations, and meanings that are part of cultural complexes that encompass language, naming and classification systems, resource use practices, ritual, and worldview. Indigenous knowledge is represented as a set of understandings, interpretations, and meanings that belong to a cultural complex that encompasses language, naming and classification systems, resource use practices, ritual, spirituality, and worldview (note: the difference is spirituality).

The Saskatchewan curriculum emphasizes cultural perspectives throughout all of their science documents stating that:

> Students should recognize and respect that all cultures develop knowledge systems to describe and explain nature. Two knowledge systems emphasized in this curriculum are First Nations and Métis cultures (Indigenous knowledge) and Euro-Canadian cultures (science). In their own way, both of these knowledge systems convey an understanding of the natural and constructed worlds, and they create or borrow from other cultures' technologies to resolve practical problems. Both knowledge systems are systematic, rational, empirical, dynamically changeable, and culturally specific. (SASK Science 9, p. 20)

The cultural perspective is carried through to the general and specific learning outcomes often in terms of identifying and/or comparing and contrasting cultural perspectives. For example, in grade 9 science, we find curriculum outcome RE9.4 "Analyze the process of human reproduction, including the influence of reproductive and contraceptive technologies" (p. 32). An indicator of achievement is given as "Acknowledge differing cultural perspectives, including First Nations and Métis perspectives, regarding the sacredness, interconnectedness, and beginning of human life" (p. 32). The achievement of these outcomes is also carried through the recommended textbook, Saskatchewan Science 9, developed especially for this curriculum. First Nations and Métis content, perspectives, and ways of knowing are an integral part of the Saskatchewan science textbook. For example, the social and cultural perspective in the section on contraception states, "All cultures and religions have moral and ethical beliefs surrounding reproduction and contraception. There are also different beliefs about when exactly a fertilized egg is considered to be a person. For this reason, some methods of contraception are considered to be the ending of a human life" (p. 103). In another section on chemical change, a cultural perspective is given as "Some medicine women would go on a fast for several days during which time they would meditate on the medicines and plants they would mix to create the desired effects. Certain families have spiritual understanding to mix medicines for heart disease, diabetes, hepatitis, and other illnesses" (p. 140). The textbook does not just pay "lip service" to cultural perspectives, but integrates differing viewpoints, Elder's wisdom, and traditional knowledge throughout all units. It should be noted that in no way does the textbook shy away from an open and clear discussion of controversial topics in science such as contraception. Given the recent publication of the textbook series, it remains to be seen how it will be accepted by students, teachers, parents, and other stakeholders.

As widely noted in educational circles, we have an intended curriculum and an implemented curriculum. Teachers remain the final filter in the delivery of any curriculum, and their professional development and preservice preparation is an important factor in the actual achievement of these outcomes in the classroom. This point reflects the practical orientation of the teaching field and what they value or at least what they believe schools and stakeholders value. Interestingly, in a study conducted by the SCC in 1980, a survey of over 4,000 science teachers in Canada ranked the importance of objectives in science education. Out of 14 different objectives, the number one was "understanding scientific facts, concepts and laws" and number 14 was "understanding the history and philosophy of science." Many teachers hold preconceptions about teaching science from their own experiences, from their preservice education experiences, and from their own teaching experiences (Duffee and Aikenhead 1992). Aikenhead suggests that "a simple in-service intervention by itself holds little promise for altering a teacher's acceptance of STS science" and argues that in addition to changing deep-seated values and images of teaching science, teachers must add new methods to their repertoire of instructional strategies. However, his recommendation that new routines of instruction are best learned from fellow teachers means we must provide meaningful preservice instruction to develop these teachers. In the next section, I'll outline a couple of exemplars oriented towards developing new "routines of instruction" in preservice teachers.

62.6 Teacher Education

Teacher education and certification in Canada is governed by each provincial or territorial agencies through regulations established by colleges of teachers and/or ministries of education. At the university level, teacher education programs must be designed to meet these specific requirements in terms of required coursework and practical teaching experience. Teacher education programs in Canada generally have two forms: an integrated program or an after-degree program.[5] In the integrated program students enter directly into a faculty of education and take subject area courses at the same time as they take education courses. Typically, the majority of the education courses can be found in the final 2 years of the program; at this time students complete an in-school practicum which varies in duration from province to province. In after-degree programs, students first complete a degree and then enter a 12-month or a 24-month education program (depending on provincial requirements). In both the integrated and after-degree programs, students typically finish with two degrees, a subject area general bachelor degree and a bachelor of education degree (although some programs may vary).

In terms of course offerings, students in education programs will take courses in educational psychology, teaching methodology, literacy, aboriginal education, special education, plus curriculum, instruction, and assessment in their teaching specialties. Teacher programs, in both the integrated and after-degree format, can be very crowded places in terms of compulsory requirements that vary from province to province. Some education professors across the country who maintain an interest in HPS may be found to include the nature of science as a lecture or topic in their methods courses. However, it is unusual to find a course offering in the history and philosophy of science and science teaching at the undergraduate level.[6] Therefore, I offer here two exemplars in teaching the history and philosophy of science and science teaching that is required at the undergraduate level. The first is a course for secondary preservice science teachers who have a major or minor specialty in the sciences. The second exemplar is a course for nonspecialist middle-year teachers.

62.6.1 HPS for Secondary Science Teachers

The history and philosophy of science and science teaching course, developed and taught by the author, is offered at the University of Winnipeg and is compulsory for all students with a double science major/minor. The course can also be taken as an elective by other interested students. The course has essentially three components, philosophical perspectives in science, teaching strategies for HPS, and a historical case study (Stinner et al. 2003). Using a seminar format, students examine, chapter by chapter, John Losee's (1993) book, *Introduction to the History and Philosophy of Science*. Losee contends that the philosopher of science seeks answers to such questions as:

What characteristics distinguish scientific inquiry from other types of investigation?
What procedures should scientists follow in investigating nature?

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[5] There are many variations of these programs across the country, including specialized access programs.

[6] It is possible from time to time to find graduate courses that relate specifically to HPS themes. For example, Derek Hodson offered a graduate course, Curriculum Making in Science: Considerations in the History, Philosophy, and Sociology of Science.

What conditions must be satisfied for a scientific explanation to be correct?
What is the cognitive status of scientific laws and principles?

Providing a commentary on original works from Aristotle to Van Frassen (and everyone in between), Losee's approach is appropriate for the undergraduate student and provides an insight into the major questions in the philosophy of science. Following the grounding in the philosophy of science, a number of teaching strategies are examined including the implementation of historical experiments, storytelling, debates, and a variety of differentiated instruction strategies (Metz et al. 2007). Students complete their own case study that traces the historical development of a scientific idea and design a plan to implement instruction in a science class. Case studies over the years have included all of the major ideas in science such as the development of the models of the atom and the cell and the history of pasteurization. However, many creative, unique, and interesting case studies have also been developed that include the history of the pacemaker, birth control, the story of blood, play doh, and climate change.

62.6.2 HPS for Nonspecialist Middle-Year Science Teachers

In teacher education programs in Canada, preservice middle-year programs typically follow a set of standard courses in content area pedagogy. As generalists, these teachers are faced with teaching a broad range of subjects with a core of language arts, social studies, mathematics, and science. Students, who enter these programs, overwhelmingly, have a background in the humanities. Very few students have a background in mathematics and science, and their self-efficacy in teaching these subjects is generally low.

As a model program incorporating HPS, I will outline here a middle-year science methods course initiated by Brian Lewthwaite at the University of Manitoba (Lewthwaite 2012). Recognizing that their teacher candidates viewed science as primarily a body of knowledge and not a process of inquiry, they use the nature of science as a pedagogical framework to assist their students in developing a more authentic view of science:

> More importantly, we believe it has the potential to assist teacher candidates in developing a positive self-image of themselves as teachers of science because their role is focused more on an understanding of the pedagogical processes to be employed in science instruction rather than, simply, their content knowledge. (Lewthwaite 2012)

In their course, suitable topics are identified for students to teach in their practicum experience that follows the course. The course instructor would then present a historical account of the development of understanding associated with the topic under consideration in a 1-h presentation. Following the presentation, the students were asked to consider the nature of science (NOS) attributes embedded within the historical context. Next, the student teachers, working in pairs, planned three linked authentic science lessons that addressed the topic to be taught. The students were required to use their understanding of the nature of science as a rationale for the task orientation taken in the lesson. Following the course, students participate in a 5-week teaching practicum where they co-teach their lessons. In a post-teaching reflection, the students are required to identify at least five nature of science characteristics that they believed informed the development of their lessons and their teaching of science. Additionally, the students critiqued their own lessons and reported on how these attributes resulted in positive learning experiences for their students.

Initial results of this innovative program have been very positive (Lewthwaite 2012). Their students speak of transformative experiences viewing science as a human activity, focusing on educational goals that are social and personal and an instructional emphasis that is more process oriented. The authors make a strong claim that NOS must not just be an ad hoc component of a science methods course for middle-year teachers but that

> NOS needs to be the foundation upon which teacher education science courses should be premised, especially in using the human story of science as vignettes for teacher candidates to come to an appreciation of what science is. (Lewthwaite 2012)

62.7 Conclusion

Canada, as a country, is geographically very expansive and culturally highly diverse. In many ways, it is difficult for outsiders to imagine how the nation brings such a diverse set of ideas together into a national perspective. In reality, we never do. Within the most recent round of curriculum renewal, provinces interpret and implement the national standards in their own, sometimes unique, ways.

It is clear from our review of HPS perspectives in Canadian curriculum and teacher education that we have made significant progress in enabling the inclusion of HPS perspectives in science education today. A great deal of attention is being given, especially in the academic community, to STSE and sustainable initiatives. Additionally, cultural perspectives, especially as noted in the province of Saskatchewan, are being integrated in a significant manner. However, it is also evident that more work needs to be done to prepare teachers to teach STS, HPS, and cultural perspectives such that the intended curriculum more closely matches the implemented. Most elementary and middle-year school teachers still have little science background, and most teachers still give low priority towards teaching the more subtle aspects of HPS. Unfortunately, knowledge content is still the emphasis in science education today dominated by teacher-directed instruction and motivated in a large part by assessment techniques. As we move forward, we are thankful for the appearance of HPS in national documents and initiating, at least in part, a national discussion.

Further studies are needed to demonstrate the effectiveness of HPS perspectives and the extent to which it can be a guiding principle as advocated by Lewthwaite instead of merely an “add-on” to traditional science instruction. Probably, the most interesting period of curriculum reform lies ahead.

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Chapter 63
History and Philosophy of Science and the Teaching of Science in England

John L. Taylor and Andrew Hunt

63.1 The Years Leading Up to the National Curriculum

Interest in teaching about the history of science and aspects of its philosophy in schools dates back, in the UK, at least as far as the mid-nineteenth century. In his exploration of the claims made for the teaching of the history of science, Edgar Jenkins (1990) quotes from the presidential address at the British Association for the Advancement of Science meeting in Glasgow in 1855. The Duke of Argyll said that what was wanted in the teaching of the young, was 'not so much the mere results, as the methods, and above all, the history of science', if education were to be 'well-conducted to the great ends in view'.

In a review, Michael Matthews (1994/2014) traces the weak and uneven tradition of incorporating the history of science in science education and takes up the story at the start of the twentieth century when, in 1918, a committee chaired by J J Thomson issued a report called *Natural Science in Education* which argued that:

> It is desirable…to introduce into the teaching some account of the main achievements of science and of the methods by which they have been obtained. There should be more of the spirit, and less of the valley of dry bones…One way of doing this is by lessons on the history of science (Cited in Brock (1989, page 31)).

The report went on to say that:

> some knowledge of the history and philosophy of science should form part of the intellectual equipment of every science teacher in a secondary school.

As Mathews has shown, these recommendations were included in the 'Science for All' curriculum that was developed after the First World War. Also in the

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interwar years, Percy Nunn, the philosopher of science, Richard Gregory and other historically minded educationalists argued the case for history. Popular science textbooks incorporating these ideas were written by a number of authors including the chemist, E. J. Holmyard. Holmyard argued for a historical approach, not just on motivational or instrumentalist grounds but on cognitive grounds: teaching a topic historically was the only way that the nature of scientific truth could be conveyed.

After the Second World War, the history of science gradually diminished in importance in school science. Science education was subject-focussed and directed towards external examinations controlled by the universities. By modern standards, this was a small-scale business. In 1952 only about 20,000 candidates, aged 16, took O-level Biology with about 15,000 taking O-levels in each of physics and chemistry (ASE 1979). These examinations were taken by a subset of the students attending selective grammar and independent schools which catered for about 25 % of the age cohort.

At that time, most young people attended secondary modern schools and left at the age of 15 with no qualifications in science. However, during the late 1950s and early 1960s, some local authorities began to move away from the selective system and establish comprehensive schools. By the late 1960s, comprehensive secondary education had become a central part of government policy. In the same decade, new regional examination boards were set up to provide the Certificate of Secondary Education in all subjects, including science, for young people who were not able to take O-levels.

Then, in 1972, the school leaving age was raised to 16. From that time on, most students were expected to take CSE or O-level examinations before leaving school or staying on for further education. As a result of these developments, more and more young people chose to study some science throughout their time in secondary school. Subsequently, in 1989, the study of science became a compulsory part of the curriculum with the total number of students gaining science qualifications at the age of 16 exceeding 600,000 per year by the twenty-first century.

The tradition established in selective schools continued to be very influential. In this tradition, school science was regarded as a fixed body of knowledge, related to and derived from real science, which young people need to acquire in order to understand the world they live in and which they must master in order to take their studies of science further (ASE 1979). The persistence of this general approach meant that teaching about the history and nature of science did not enter the mainstream of science education for all in England and Wales until the national curriculum was introduced in 1989 (Department of Education and Science 1989).

The first version of the curriculum was detailed and complex. It was divided into 17 attainment targets (ATs). One of the significant innovations was the seventeenth attainment target, AT17 ‘The nature of science’. The intention of AT17 was that students should study historical case studies to develop their understanding of how scientific theories arise and change through time. They were also expected to explore how the nature and application of scientific ideas are affected by the social and cultural context in which they develop.

None of the ideas in AT17 were new, but for the first time it was compulsory that they should feature in the science courses of most learners. The feasibility of teaching these ideas, and the resources needed for the teaching, had been investigated on a relatively small scale in a series of innovative curriculum projects during the previous three decades starting with the Nuffield projects of the 1960s.

63.2 Nuffield O-Level Sciences in the 1960s

By the mid-1950s, it had become clear to teachers and politicians that secondary science education was in need of major reform. There was dissatisfaction with the emphasis on factual recall in examinations. Chemistry courses focussed on the preparation and properties of elements and compounds, whilst in physics the content was largely confined to the classical themes of nineteenth century science such as electricity and magnetism, heat, light and sound. Biology, as a combination of botany and zoology, was not fully established as a subject for boys as well as girls (Hunt 2011).

Pressure for change arose particularly from activists in the Science Master's Association and Association of Women Science Teachers (organisations which merged to form the Association for Science Education in 1963). Leading teachers from selective schools had built up a consensus that there was an urgent need to modernise both the content of the science curriculum and how it was taught. Much work had been done in the late 1950s to draw up fresh syllabuses.

The problem was that at that time there was no statutory, centralised control of the curriculum. The government did not expect to intervene directly in curriculum matters. As a result, there was no established way to bring about reform and no obvious source of resources to fund the development work. However, after a period of negotiation, the Nuffield Foundation[1] decided to make a very large grant towards the cost of a long-term programme to improve the teaching of school science and mathematics. This was the beginning of a major era of curriculum development

The work began with the Nuffield Science courses to O-level. These were very influential, but their main focus was on practical work carried out by students as the starting point for introducing scientific concepts. Nevertheless these courses did not ignore the tradition of using episodes from the history of science as a context for teaching science. One of the aims of Nuffield Biology,[2] for example, was to present the subject as part of human endeavour showing, with the help of historical examples, that biological knowledge is the product of scientists working in many different parts of the world (Nuffield Foundation 1966a). The course aimed to demonstrate that the science of biology is based not only on observation and experimentation but

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[1] The Nuffield Foundation website has an account of the charity's involvement in the science curriculum over 50 years: http://www.nuffieldfoundation.org/curriculum-projects

[2] All the original Nuffield Biology publications are available from the National STEM Centre eLibrary at http://stem.org.uk/cxhs

also on questioning, the formulation of hypotheses, testing of hypotheses and, above all, on communication between people.

Nuffield Chemistry[3] aimed to encourage students to be ‘scientific about a problem’ (Nuffield Foundation 1966b). This was based largely on the project team’s perception of what ‘being scientific’ means to a scientist: the application and the personal commitment involved, the importance of the disciplined guess or ‘hunch’ as well as logical argument, the feeling of exploration and the readiness to make apparently unwarranted jumps whilst knowing how to check their validity.

The Nuffield Chemistry project produced an extensive series of Background Books for students which were intended to amplify and extend work done in class and to stimulate the interest of pupils in wider aspects of their study. Many of these short readers were historical featuring the work of famous scientists from the early nineteenth century to the mid-twentieth century. *The Way of Discovery*, one of the Stage III Background Books, began with a short statement about the origins of scientific knowledge as an introduction to a series of personal accounts based on interviews with 14 Nobel Prize-winning scientists.

However, there were no explicit learning outcomes about the nature of science. Understanding of the methods of scientific enquiry was treated as a tacit aspect of science learning (Millar 1997). There was no significant credit in the O-level examinations for this kind of learning.

Nuffield Physics,[4] like the other Nuffield courses, was committed to presenting the subject as a connected fabric of knowledge with a focus on key concepts (Nuffield Foundation 1966c). Under the influence of Eric Rogers, the project team wanted students to acquire the feeling of doing science, of being a scientist – ‘a scientist for the day’. As with the other courses, the teaching approach was based on a guided introduction to physics concepts related to hands-on practical work by learners. Even so, the history of physics was of particular importance in the fifth year of the course which traced the development of theories about the solar system from ancient Greek models to the grand Newtonian synthesis (Nuffield Foundation 1966d). However, as the Teachers’ Guide to Year V shows, the main focus of the teaching was on Newton’s laws of motion, circular motion and other related concepts.

Paul Stevens was one teacher who explored the contradictions between the ‘discovery learning’ encouraged by the Nuffield courses and the ultimate aim of teachers to induct their students into the accepted scientific explanations (Stevens 1978). He argued that there was a logical conflict between ‘discovering’ and ‘learning’ which could produce some undesirable psychological results. In his view the fragmentary Nuffield philosophy, in so far as it could be abstracted from the publications, was bound to influence teachers into misleading students about the nature of science.

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[3] All the original Nuffield Chemistry publications, including the Background Books, are available from the National STEM Centre eLibrary at http://stem.org.uk/cxew

[4] All the original Nuffield Physics publications are available from the National STEM Centre eLibrary at http://stem.org.uk/cxqc

Jonathan Osborne (2007) has also pointed out that Eric Rogers' vision of what it means to be a 'scientist for a day' was a very narrow one based predominantly on the exact sciences of physics and chemistry and a hypothetico-deductive methodology. Osborne also gives examples to show why it was wrong to think that the learning of science and the doing of science could be regarded as one and the same thing. Whilst the practice of science is the search for answers concerning unanswered questions that we have about the material world, the task of science education is different. Its role is to construct in the young student a deep understanding of a body of existing knowledge.

63.3 Integrated and Process Science

Another course devised for more able learners was the Schools Council Integrated Science Project (SCISP),[5] known as *Patterns*, which was designed as a 3-year course to O-level for 13–16-year-olds (Schools Council 1973). This was developed in the late 1960 and early 1970s with the aim of providing a broad and balanced science curriculum in about a fifth of the available curriculum time in schools. That is the time that was typically allocated to two of the three traditional science subjects.

The rationale for integration was that all scientists use the same general approach to their work: the 'art' of science that is common to all areas of the subject. In *Patterns* this 'art' was expressed in terms of 'pattern-seeking' and 'problem-solving'. Throughout the scheme, students were expected to search for generalisations which could be expressed as patterns. These patterns were then used to solve scientific problems.

The American psychologist Robert Gagné was a major influence on SCISP. His thinking shaped the pedagogy and also helped to justify the notion that the content of science did not matter. His view was that knowledge was evolving so rapidly that anything learnt today might be redundant tomorrow. The enduring features of science were its processes. Hence, what young scientists needed to learn were processes: measurement, observation, hypothesis generation, experimental design and so on (Adey 2001).

The SCISP project team pointed out that they were not presenting their approach as *the* 'scientific method'. However, in later projects such as *Warwick Process Science* (Screen 1987) and *Science in Process* (Inner London Education Authority 1987), there was even more emphasis on a common set of scientific processes such as observing, classifying, inferring, investigating, predicting, hypothesising and evaluating. In these courses there was a clear implication that these activities in school reflected the ways in which scientists work across a wide range of scientific disciplines.

Unlike SCISP, these later integrated and process-based science courses, published in the 1980s, were planned in order to offer something to students across the ability

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[5] All the original Schools Council Integrated Science Project publications are available from the National STEM Centre eLibrary at http://stem.org.uk/cxug

spectrum in the expectation that the most able students would find challenge in working at processes and meet the demand for problem-solving with sophistication, whilst the less able students would find the work stimulating without experiencing failure and consequent disillusionment with science.

However, this particular view about the nature of science was later criticised by Paul Black (1986) in his presidential address to the Association for Science Education. He warned against the temptation for curriculum planners to invent their own theories of knowledge, of philosophy and of culture. He pointed out that the philosophy of biology has its own agenda, distinct from the philosophy of physics, dealing, for example, with questions of reductionism, the general problem of teleology, the notion of organicism and whether or not biology can claim to have its own distinctive laws. One of the principles for curriculum design in science, he suggested, is that teaching should acknowledge the diversity and spectrum of differences across the sciences.

Robin Millar and Rosalind Driver (1987) in an article called *Beyond Process* presented a detailed critique of the assumptions that were being used at the time, more or less implicitly, as a basis for the case for 'process science' and which were, in their view, in danger of luring science educators along a misguided path. In examining the 'processes of science' from the perspective of the philosophy of science, they argued that there is no evidence to support the view that there is a unique and distinctive method of science based on a set of generalisable processes.

63.4 Science, Technology and Society (STS) Courses

In the mid-1970s science teachers recognised a fresh challenge. Despite the development work of the previous decade, young people were not opting for science. The term 'flight from science' had become current since the publication of the 1968 Dainton Report which had shown that the number of students studying science in the upper secondary school was declining. Some of the teachers who had taken leading roles in Nuffield projects, including John Lewis, a physics teacher in a selective independent school, surmised that they had enjoyed themselves too much investigating the intellectual niceties of theoretical science, when they should have been more concerned with the interplay between science and society (Lewis 1987). However, at the time, most science teachers felt ill-equipped to present a broader view.

In response the Association for Science Education gave support to two curriculum development projects in England that produced Science, Technology and Society (STS) courses for school students (Aikenhead 1994; Hunt 1994). One of the STS course was 'Science in Society', which was led by John Lewis (1981).[6] This course was strongly influenced by the 'Club of Rome' report on the limits to global

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[6] The *Science in Society* Teacher's Guide and Readers are available from the National STEM Centre eLibrary at http://stem.org.uk/cx9s

growth (Meadows 1972). The other was 'SISCON in Schools'[7] headed by Joan Solomon (1983), then a teacher in a state school. Her team drew inspiration from SISCON – Science In a Social CONtext – that had been inaugurated in 1971 for students in universities and polytechnics.

Both these courses were able to innovate and experiment with new themes because they were studied by post-16 students in the slot in the timetable for general studies intended to broaden the curriculum for those taking two or three specialised academic A-level courses. Teachers had a great deal of freedom in their choice of courses to run as part of general studies because they did not count for much outside schools.

The place of the science in STS courses was a matter for debate (Solomon 1988). Research had suggested that students were often resistant to accepting and applying scientific knowledge in the context of social issues because they had difficulties in reconciling the uncertainties of the issues with what they perceived as science's claims to 'truth' (Aikenhead 1987; Fleming 1986). This led to the view that in STS courses it was important that students should learn something about the nature of scientific theories. Proponents of STS courses argued that students needed to appreciate the role of imagination in the development of theories, the importance of modelling and the relationships between data and explanations. In addition it was suggested that students needed to appreciate something about the provisional and uncertain nature of scientific theories.

Science in Society Reader J called *The Nature of Science* featured essays by a range of authors. One essay contrasted Baconian induction with the views of Karl Popper on the scientific method. Another essay in the reader outlined the ideas of Thomas Kuhn on how scientific ideas develop. Other essays dealt with the role of imagination in science and with the interfaces between science and religion. Reader K *Science and Social Development* opened with an essay by Sir Desmond Lee included a discussion of the extent to which Greek speculation about the nature of the physical world could be regarded as scientific in the modern sense of the term.

The nature of science was explored in the SISCON reader called *How can we be sure?* which included chapters about observations and generalisations and about the birth of scientific theories. This reader also included a historical section about changes in scientific explanations such as changes in theories about light and about burning.

In his review of the rationale for STS courses, John Ziman (1994) discussed the diversity of approaches to STS. In his view, the fundamental purposes of STS education were genuinely and properly diverse and incoherent. He identified and commented on seven different approaches drawn from STS initiatives around the world including the historical approach and the philosophical approach both of which had featured to a limited extent in the English STS programmes.

Commenting on the historical approach, Ziman noted that the history of science had long been regarded as the most natural medium for humanising science education

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[7] The *Science In a Social CONtext* Teachers' Guide and a series of Readers are available from the National STEM Centre eLibrary at http://stem.org.uk/cx9z

but that this was not without serious disadvantages. One disadvantage was that since the actual history of science is peculiarly deep, subtle and complicated, for most students the history of science is just too academic and remote. This leads to a related disadvantage, namely, that elementary accounts of the history of science in school end up as historically inaccurate celebrations of scientific progress which attribute heroic qualities to a few exceptional individuals. This echoes Stephen Brush's concern that the history of science in schools all too often leads to fictionalised idealizations and conveys a view of history that implies that science is a steady and cumulative progression towards the pinnacle of modern achievements (Brush 1974). Despite these warnings, teachers and curriculum developers continued to feature historical case studies whilst generally ignoring the new historical interpretations.

The two pioneering post-16 STS courses were only adopted by a small minority of students for study after the end of their compulsory period of education. Nevertheless, they proved influential because the resources they published helped to introduce teachers to ways of linking their science teaching to the world outside school or college. The projects also featured new teaching approaches for engaging the interest of their students in issues related to the nature of science and its applications (Lewis 1987). Curriculum developers who had been involved in these projects were soon taking leading roles in the Science, Technology in Society (SATIS) projects. These were very much more widely adopted and later were major influences on the first version of the national curriculum.

63.5 The SATIS Projects

Michael Young (1971), when discussing the stratified and specialised nature of the traditional school curriculum, contrasted the closed, narrow, high-status curriculum suited to potential future science specialist (such as the Nuffield O-level schemes) with open, broad, low-status programmes for the rest. He argued that under this regime it was inescapable that most of those who succeeded in school science would be systematically denied the opportunity to grasp science as an integral and unavoidable part of social life, whilst the rest, the failures, would leave school to become members of a scientifically illiterate public.

By the early 1980s this view was becoming more widely shared as shown by the first UK government statement about the science curriculum which made the case for broader, less specialised science programmes in school (Department of Education and Science 1985). This statement defended the proposed changes by claiming that science courses could challenge able students not by the task of accumulating greater stores of scientific knowledge but by the application of scientific principles to the real world, by the opportunity to investigate and solve problems and by the necessity of bringing scientific method to bear on assignments where the answer cannot be predicted in advance.

In line with the official guidance, significant changes in science education took place. In many schools, the option to study one, two or three of the separate sciences was replaced by compulsory science courses occupying 20 % of curriculum time from the age of 14 to the age of 16. These programmes of ‘balanced science’ were variously integrated, co-ordinated or combined, but, like SCISP, they had the common aim of making sure that all young people continued to study elements of biology, chemistry and physics as well as other aspects of science such as earth science and astronomy throughout their secondary education. This could be a challenge for teachers who were no longer working with students who had chosen to study their specialist subject.

Also at this time, the old system of public examinations for 16-year-olds (based on O-levels and the CSE) was being replaced by the new General Certificate of Secondary Education (GCSE) for all young people in schools. For the first time national criteria were introduced to control the new GCSE syllabuses. Amongst other things, the criteria for science required that not less than 15 % of the assessment of science should be related to the technological applications of the subject with their social, economic and environmental implications.

In this context, the Association for Science Education (ASE) launched the first Science and Technology in Society (SATIS) project in 1984 with the support of a charitable trust and a range of industrial companies (Hunt 1988). John Holman was appointed as director having played a key role in the *Science in Society* project. The small team recruited to the project was made up mainly of teachers. Despite the imposition of the new GSCE criteria, teachers still had the expectation that they could shape the interpretation of the new courses in schools.

The team decided to develop a bank of short resource units. Each unit related to a major topic in science syllabuses whilst exploring important social and technological applications and issues. Almost all of the units were written by a larger number of contributing teachers, often in co-operation with experts from industry, higher education, agriculture or the public services. In this way the project brought new stories, case studies and examples into science education. Between 1986 and 1991 the project published 120 units each requiring a lesson or two of class time.[8]

The SATIS units were not developed according to a predetermined plan, but, in response to the coverage of GCSE syllabuses and examinations, they clustered into themes such as materials, energy resources, the environment, health and ethical issues. None of the units in this project dealt with the nature of science because this did not feature in the GCSE courses at that time. However, there were some historical units thanks to contributions from the historian, Anthony Travis (1993), a former science teacher, whose research was focussed on the origins of the chemical industry, notably the dyestuffs industry.

As a result, the project published units about the work of Fritz Haber (number 207), the discovery of Perkin’s mauve (number 510), the quest for medical ‘magic bullets’ by Paul Ehrlich (number 805) and the ingenious contributions of Carl Bosch to the commercialisation the Haber process (number 810). These units did not

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[8] All the SATIS units together with a General Guide for Teachers and an update of the first 100 units are available from the eLibrary of the National STEM Centre (Accessed in March 2012 from http://stem.org.uk/cx9n)

present a particular view of the nature of science but touched on the human side of scientific discovery and the social implications of technological changes.

The units were presented in the form of short teachers' notes with student worksheets which schools were free to copy. ASE was able to publish the units cheaply at just the right time with the result that they were very widely adopted. This form of publishing became very popular in the UK and other projects adopted a similar pattern. Between 1995 and 1999, for example, ASE produced a series of SATIS-style units to celebrate key centenaries in the history of science.[9]

Following the success of the first SATIS project, the ASE decided to extend the work to older students. The new project, SATIS 16–19, was similar to SATIS in many ways: it was funded on a similar basis, teachers determined the policy and did the writing, and the intention was to produce a bank of varied resource materials to enrich existing courses. The project team set out to support both the general education of all students as well as to provide resources to supplement specialist science programmes.

In addition to the 100 SATIS 16–19 units[10] published between 1990 and 1992, the project also published three readers written by Joan Solomon which were designed to provide a rationale for planning the STS component in programmes of general education. The first of the readers, *What is Science?*, encouraged students to reflect on the nature of scientific theories and to consider where imaginative scientific theories come from. Examples from the history of science were included to show how scientific theories change and to explore the interplay between science and society. The sections of this reader were cross-referenced to related SATIS 16–19 units, allowing students to examine selected topics in more depth. The related units included *The retrial of Galileo* (unit 1), *Two games and the nature of science* (unit 26), *Patterns in the sky* (unit 51), *Why do we grow old?* (unit 61) and *Science and religion – friends or foes?* (unit 77).

An important aspect of these two SATIS projects was the way that they helped to legitimise activities which had not previously been common in science lessons. The units provided teachers with models for lessons involving discussion techniques, role plays, analytical reading, data analysis and problem-solving. These approaches to teaching and learning were essential in broadening school science to encompass historical topics and studies of the nature of science.

Following their experience with STS and SATIS projects, John Holman and Joan Solomon went on to make significant contributions to the development of the first national curriculum for England and Wales. John Holman was a member of the core working group that drafted the new curriculum, and Joan Solomon acted as adviser for the development of AT17.

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[9] See the four units in the collection called 'Celebrating Centenaries of Famous Discoveries' in the eLibrary of the National STEM Centre (Accessed in March 2012 from http://stem.org.uk/cxg6)

[10] All the SATIS 16–19 units together with the three readers, *What is Science*?, *What is Technology?* and *How does Society decide?*, are available from the eLibrary of the National STEM Centre (Accessed in March 2012 from http://stem.org.uk/cxas)

63.6 The Nature of Science in the National Curriculum

The first version of the national curriculum for England and Wales was introduced in 1989. It was divided into 17 strands, called attainment targets (Department of Education and Science 1989). Two of these attainment targets conveyed generic messages about science: AT1 Exploration of Science and AT17 The Nature of Science. Jim Donnelly (2001) has discussed the tensions between AT1 which drew on a broadly empiricist and inductivist tradition in science education and AT17 which was strongly influenced by STS thinking with its emphasis on the social and cultural dimensions of science.

Professor Jeff Thompson was chair of the working group that drafted the science curriculum. He had been active in the Association for Science Education and 10 years earlier had chaired the ASE group that wrote the consultative document *Alternatives for Science Education* (ASE 1979). This report had aimed to anticipate possible developments in the structure of the science curriculum by describing three possible curriculum models. All three models included aspects of the history and philosophy of science. Thus the chair and several members of the national curriculum group had an interest in introducing AT17 despite the challenge that this would present to many science teachers.

Stephen Pumfrey's critique (1991) of this first version of the national curriculum concentrated on AT17. He pointed out that a curious feature of this attainment target was that it nowhere gave an explicit answer to the question ‘What is the nature of science?’ He suggested that these nine ideas were the key ingredients of what the answer implied by AT17 appeared to be:

1. Meaningful observation is not possible without a pre-existing expectation.
2. Nature does not yield evidence simple enough to allow one unambiguous interpretation.
3. Scientific theories are not inductions, but hypotheses which go imaginatively and necessarily beyond observations.
4. Scientific theories cannot be proved.
5. Scientific knowledge is not static and convergent, but changing and open-ended.
6. Shared training is an essential component of scientific agreement.
7. Scientific reasoning is not itself compelling without appeal to social, moral, spiritual and cultural resources.
8. Scientists do not draw incontestable deductions, but make complex expert judgements.
9. Disagreement is always possible.

In exploring these ideas, students were expected to learn about stories from the history of science. Pumfrey highlighted tensions implicit within AT17 which, on the one hand, recognised that there have been different values and forms of natural knowledge in different times and contexts whilst, on the other hand, expecting historical case studies to illustrate the norms of scientific practice today.

Pumfrey illustrated his arguments with reference to teaching resources developed under the leadership of Joan Solomon. She had not only contributed to the formulation of AT17 but also had been one of the people who led initiatives to support its implementation in schools. Her first publications were short readers telling stories about developments in the history of science written for 11–14-year-olds to illustrate aspects of the nature of science.[11] Next she worked with groups of teachers in schools to devise a varied collection of teaching and learning activities covering all the aspects of AT17. These lesson ideas were published in two volumes called *Exploring the Nature of Science*: one for 11–14-year-olds (Key Stage 3) (Solomon 1991) and one for 14–16-year-olds (Key Stage 4)[12] (Solomon undated).

Many of the activities in *Exploring the Nature of Science* were based on historical case studies. The introduction to the Key Stage 3 book shows that the authors were sensitive to the tensions identified by Stephen Pumfrey by stating that:

> The greatest difficulty with teaching history is understanding just what scientists in another age meant by the terms they used – like ‘atoms’, ‘heat’ or even ‘…made of water’. In none of these cases were the meanings exactly as they are today. The subtlety of historical research lies in trying to understand the thinking of scholars who were influenced by philosophies that few of us have even encountered. Inevitably we are forced to simplify, both through lack of time, and because our basic intention is not to lecture on the history of science, but to teach children about the nature of science (Solomon 1991, Introduction – *no page numbers*).

The Nuffield-Chelsea Curriculum Trust[13] had also responded to AT17 with a publication called *Investigating the Nature of Science.*[14] The file was devised by a team from King’s College London. It aimed to support teaching of all aspects of AT17 to 11- to 16-year-olds. The resource provided detailed lesson ideas covering 12 topics explored with the help of a variety of methods that included discussion, role-play, experimental work, models and guided reading (Honey 1990).

This file contained an introduction to explain the rationale of AT17. This began with a discussion of the reasons for covering the nature of science in a science course. The authors pointed out that a view of the nature of science is implicit in any science course and suggested that it is desirable to articulate and clarify what this view is so that, for example, students understand better the relationships between experiments and theory.

The introduction to the file went on to explain how misconceptions about science can arise in the minds of learners both from messages in the media and from the

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[11] The *Nature of Science* readers were published by the Association for Science Education (1989–1990), and most of them are now available from the eLibrary of the National STEM Centre (accessed in March 2012 from http://stem.org.uk/cx9r)

[12] The *Exploring the Nature of Science* publications are available from the eLibrary of the National STEM Centre at http://stem.org.uk/cxfb

[13] From the late 1970s to the early 1990s, the Nuffield Foundation’s support for curriculum development in science, maths and technology education was the responsibility of the Nuffield-Chelsea Curriculum Trust based at Chelsea College.

[14] *Investigating the Nature of Science* is available from the National STEM Centre eLibrary at http://stem.org.uk/rx3a7

experience of school science. Finally the authors reviewed some differing views about the nature of science before suggesting ways of making the history and philosophy of science part of the school curriculum.

63.7 The Short Life of AT17

The first version of the science national curriculum was so detailed and complex that a revision began very soon after it was launched in schools. Given the many demands made by the new curriculum, and the lack of expertise and limited resources for teaching AT17, there was little opposition when, in 1991, this attainment target was merged with the first attainment target (AT1) that covered investigative practical science (Department of Education and Science 1991).

It is not surprising that few teachers regretted the passing of AT17 in view of the argument put forward by Martin Monk and Jonathan Osborne (1997). They suggest that the failure of the history of science to contribute to the mainstream of science teaching arises because teachers have no confidence that a historical context adds anything to their students' knowledge and skills. Within the classroom, teachers' dominant concerns are the development of the student's knowledge and understanding of the content of science; that is with 'what we know' rather than 'how we know'. Many teachers also lack the requisite knowledge of either the history of science or the nature of science to explore any of these issues appropriately. Teachers are heavily influenced by the demands of external assessments. The early national curriculum tests did little to support the teaching of AT17.

63.8 Rethinking the Purposes of Science Education: Beyond 2000

The first major review of the national curriculum as a whole was carried out by Sir Ron Dearing, a former senior civil servant who had recently been chief executive of the Post Office Ltd. His report (Dearing 1993), published in 1993, argued that the curriculum had become an unwieldy structure which was virtually impossible to implement. As a result a further revision was carried out to cut down the content and to eliminate overlap between subjects. Coverage of the nature of science was reduced in emphasis in the resulting 1995 version of the science curriculum (Department of Education and Science 1995). The consequence was that there was little or no attention given to teaching about the history of science and the nature of science by most teachers in pre-16 courses for the next 10 years or so.

Following the Dearing review, the government announced a 5-year moratorium on curriculum change. This provided an opportunity for reflection which was taken up by Rosalind Driver and Jonathan Osborne of King's College, London. A grant from the Nuffield Foundation provided the support for a seminar series to 'consider and review the form of science education required to prepare young people for life in our society in the next century'.

The series of six invitation seminars were held between 1997 and 1998. In addition there were two open seminars to widen the discussion to include teachers and others with an interest in the future of science education. The *Beyond 2000* report (Millar and Osborne 1998) from the seminar series made the case for finding better ways to meet the two main purposes of science education for 14–16-year-olds:

- To develop the 'scientific literacy' of all students in preparation for adult and working life
- To provide the foundations for more advanced courses in science

The report proposed that the same curriculum could not serve both purposes, especially in the final 2 years of compulsory education. It recommended that the structure of the science curriculum should differentiate more explicitly between those elements designed to enhance 'scientific literacy', and those designed as the early stages of a specialist training in science, so that the requirement for the latter would not distort the former.

The report outlined the aims and nature of a 'scientific literacy' course. Alongside the aim of introducing young people to the major 'explanatory stories' of science about life and living things, matter, the Universe and the made world, a key aim of such a course was that it should give young people an understanding of how scientific inquiry is conducted. The report summarised the rationale for teaching 'about science' in this paragraph:

> In order to understand the major 'explanatory stories' of science, and to use this understanding in interpreting everyday decisions and media reports, young people also require an understanding of the scientific approach to inquiry. Only then can they appreciate both the power, and the limitations, of different kinds of scientific knowledge claims. They also need to be aware of the difficulties of obtaining reliable and valid data. Science issues are often about the presence or absence of links and correlations between factors and variables, often of a statistical and probabilistic kind, rather than directly causal – so young people need an understanding of these ideas, and practice in reasoning about such situations. Often the plausibility of a claimed link depends on seeing a mechanism which might be responsible – and here again an understanding of the major 'explanatory stories' of science is needed. Finally, young people need some understanding of the social processes internal to science itself, which are used to test and scrutinise knowledge claims before they can become widely accepted – in order to appreciate their importance, but also to recognise the ways in which external social factors can influence them (Millar and Osborne 1998, pp. 19–20).

The *Beyond 2000* report set out in some detail the ideas-about-science that it recommended should feature in a scientific literacy course. The authors of the report warned that these ideas-about-science represented a significant expansion of the range and depth of treatment that such issues currently demanded in the existing curriculum. As a result, they pointed out that any development based on the recommendations needed to be undertaken in collaboration with science teachers so that their introduction could be a managed process and not a sudden, and possibly unwelcome, event.

63.9 Science for Public Understanding

Following his review of the national curriculum, Sir Ron Dearing was asked to review post-16 qualifications in England, Wales and Northern Ireland including A-levels. Included in his report was a recommendation for a new Advanced Subsidiary (AS) exam to be taken after 1 year post-16 to encourage students to broaden their studies by studying up to five subjects in place of the traditional three (Department for Education and Employment 1996). This would allow students to begin their post-16 programme with, say, five AS-levels – and then choose three of these to continue to A-level. They could obtain an AS-level qualification in the two that they took for just 1 year. It was suggested that the two additional AS courses taken might complement or contrast with the main areas of the students' specialist interests.

This change to the post-16 academic curriculum threw up an opportunity to reassess existing STS courses and make a fresh start. As before, there was considerable freedom allowed for the style and content of courses intended to broaden the curriculum. These courses were not subject to the detailed national guidelines that applied to mainstream advanced courses. One of the examining boards[15] invited Robin Millar to take the lead in developing a new course (Millar 2000). He had published an article outlining his thinking which set out ideas that he was also contributing as co-author of the report from the *Beyond 2000* seminars (Millar 1996).

In this way, the AS *Science for Public Understanding* course became a test-bed for trying out a model of a scientific literacy course as described in the *Beyond 2000* report. The syllabus[16] for this new course gave the same weighting to ideas-about-science as it did to explanatory theories (Millar and Hunt 2002). The course was presented as a series of topics which provided the contexts for teaching about science explanations and about the nature of science. The topics were divided equally between issues in the life sciences and issues in the physical sciences.[17]

Some of the topics were treated historically. One example was 'Understanding health and disease' that, in part, used the work of people such as Snow, Semmelweis and Pasteur to explore ideas-about-science including the distinction between correlation and cause, the origins of scientific explanations and how the scientific community resolves the conflicts between competing theories.[18] Other topics treated

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[15] The invitation came from the Northern Examinations and Assessment Board (NEAB) which later merged with other examining bodies to form the awarding organisation that is now called AQA.

[16] Over the period covered by this chapter the older term 'syllabus' has been replaced by the term 'specifications'. Specifications are more explicit about aims, content, assessment model and grade criteria.

[17] From 2007, *Science for Public Understanding* became a full A-level subject with the name *Science in Society*. The AS specification (syllabus) for *Science in Society* is very much the same as its precursor and can be downloaded from the AQA website together with past examination papers (accessed in March 2012 from http://www.aqa.org.uk/qualifications/a-level/science/science-in-society/science-in-society-key-materials)

[18] For more details of the approach, see the revised version of the AS course textbook (Hunt 2008).

from a historical perspective were ‘Understanding who we are’ which included study of the theory of evolution and its origins and ‘Understanding where we are’ which traced the development of theories of the solar system and the Universe. The other topics in the course also introduced and applied ideas-about-science when dealing with contemporary issues, including ethical issues. The textbook included an outline of some ethical frameworks to help students discuss the issues.

The teaching approach adopted for the course drew on the experience of earlier STS courses. *Science for Public Understanding* aimed to help students understand more about the nature of science and to provide them with the skills needed to participate as citizens in debates on topical science. The course therefore expected students to develop their abilities across a wider range of concepts and skills than in most traditional science classes.[19]

The timetable for introducing the new AS courses made it possible to pilot AS *Science for Public Understanding*. The first cohorts of students took pilot examinations in June 1999 and June 2000. By this time it was becoming clear that there would be an opportunity to test out the recommendations of the *Beyond 2000* report in a set of novel GCSE courses supported by a large-scale curriculum development project that came to be called *Twenty First Century Science*. With this in mind, the Nuffield Foundation commissioned a team from King’s College London to make a study of the teaching and learning of science explanations and the ideas-about-science in *Science for Public Understanding*.

The research was carried out between 2001 and 2002. The findings were published in a report called *Breaking the mould?* (Osborne et al. 2002a). The data gathered by the research team suggested that the course had been successful in achieving its first aim: to sustain and develop students’ enjoyment of, and interest in, science. The overwhelming majority of students said that the course was both enjoyable and interesting. Furthermore, the *Science for Public Understanding* course had managed to attract students who would not otherwise have studied science post-16. It was notable that nearly 60 % of all the students were female, which the researchers suggested was a significant achievement for a course where 50 % of the content was physical science.

However, the report showed that the new course made demands on teachers’ pedagogic techniques such as the skill to run and organise effective discussions that engage all students in thinking critically about socioscientific issues. The researchers pointed out that students need to be explicitly taught, not only how to evaluate media reports about science critically but also how to construct effective arguments which are reliant on evidence rather than personal or group opinion. The report stated that the available guidance on teaching methods was inadequate.[20]

The research demonstrated that changing the culture that forms and moulds teachers is much harder than simply changing the curriculum. To bring about changes requires

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[19] Schemes of work and lesson activities originally devised for AS *Science for Public Understanding* are available as revised and updated versions from the AS section of the *Science in Society* website: http://www.nuffieldfoundation.org/science-society (accessed March 2012).

[20] The *Science for Public Understanding* (now *Science in Society*) website was developed in response to this criticism (http://www.nuffieldfoundation.org/science-society)

considerable support, effort and time. The researchers concluded that the course had begun that process and planted the seeds of a different way to teach and engage students but that enabling it to take root would require continued endeavour.

Within a year of the launch of the new AS courses, as part of Curriculum 2000, it became clear that, despite expectations, most students would opt for four rather than five AS courses. As a result the interest in 1-year AS courses, such as *Science for Public Understanding*, was less than expected, but the numbers of candidates for the exams were significantly larger than had been the case for its STS predecessors at this level.

63.10 Evidence-Based Practice in Science Education (EPSE)

Between January 2000 and June 2003, a research network, funded by the Economic and Social Research Council (ESRC), carried out four interrelated projects to improve the interface between science education researchers and teachers. The aim of the programme was to develop and evaluate several examples of evidence-based practice in science education.

The lead researchers had all been involved in the *Beyond 2000* seminar series. One of the projects set out to examine the curriculum implications of the recommendation that the aim of compulsory science education should be to develop 'scientific literacy' by providing a basic philosophical understanding of the nature of science, the function and role of data in scientific argument and how the scientific community functions (Osborne et al. 2006). This project was begun in response to the notion that a shift towards science education for citizenship implied a broadening in the range of stakeholders with a legitimate interest in determining the goals of the school science curriculum.

Accepting that the nature of science is seen by contemporary scholars as a contested domain, and given the lack of empirical evidence of consensus, the research team decided to try to determine empirically the extent of agreement amongst a group of experts about those aspects of the nature of science that should be an essential feature of the school science curriculum. The method chosen for eliciting the view of the expert community was a Delphi study (Osborne et al. 2003). In this way the researchers sought to establish consensus amongst a group made up of five representative individuals from each of these groups: leading scientists, historians, philosophers and sociologists of science, science educators, those involved in science communication and primary and secondary teachers of science.

Using three rounds of linked questionnaires, where the responses were sifted and successively commented on, the researchers determined the level of agreement amongst the experts about which ideas-about-science were so important that they should be included in school science. At the end they arrived at a strong consensus about nine common themes that are summarised in Table 63.1 (Osborne et al. 2002b).

Table 63.1 Findings of a Delphi study summarising the views of experts about those aspects of the nature of science that should be an essential feature of the school science curriculum (Osborne et al. 2002b, p. 30)

Nature of scientific knowledge

Science and certainty

Students should appreciate why much scientific knowledge, particularly that taught in school science, is well established and beyond reasonable doubt and why other scientific knowledge is more open to legitimate doubt. It should be explained that current scientific knowledge is the best we have but may be subject to change in the future, given new evidence or new interpretations of old evidence

Historical development of scientific knowledge

Students should be taught some of the historical background to the development of scientific knowledge

Methods of science

Scientific methods and critical testing

Students should be taught that science uses the experimental method to test ideas, and, in particular, about certain basic techniques such as the use of controls. It should be made clear that the outcome of a single experiment is rarely sufficient to establish a knowledge claim

Analysis and interpretation of data

Students should be taught that the practice of science involves skilful analysis and interpretation of data. Scientific knowledge claims do not emerge simply from the data but through a process of interpretation and theory building that can require sophisticated skills. It is possible for scientists legitimately to come to different interpretations of the same data and, therefore, to disagree

Hypothesis and prediction

Students should be taught that scientists develop hypotheses and predictions about natural phenomena. This process is essential to the development of new knowledge claims

Diversity of scientific thinking

Students should be taught that science uses a range of methods and approaches and that there is no one scientific method or approach

Creativity

Students should appreciate that science is an activity that involves creativity and imagination as much as many other human activities and that some scientific ideas are enormous intellectual achievements. Scientists, as much as any other profession, are passionate and involved humans whose work relies on inspiration and imagination

Science and questioning

Students should be taught that an important aspect of the work of a scientist is the continual and cyclical process of asking questions and seeking answers, which then leads to new questions. This process leads to the emergence of new scientific theories and techniques which are then tested empirically

Institutions and social practices in science

Co-operation and collaboration in development of scientific knowledge

Students should be taught that scientific work is a communal and competitive activity. Whilst individuals may make significant contributions, scientific work is often carried out in groups, frequently of a multidisciplinary and international nature. New knowledge claims are generally shared and, to be accepted by the community, must survive a process of critical peer review

63.11 School Science and the Changing World of the Twenty-First Century

A new version of the whole national curriculum for England was published in 2000, but there was little change to the science curriculum. The main change was a modification of the section about scientific enquiry to incorporate some new content covering ‘ideas and evidence’.

Influenced by the *Beyond 2000* report, the government asked the Qualifications and Curriculum Authority (QCA) to begin a project which it called ‘Keeping School Science in Step with the Changing World of the twenty-first Century’. The QCA was responsible for curriculum in England at that time. By now it had become very difficult for school teachers to take the initiative and shape the core curriculum through their active membership of the Association for Science Education. Politicians and regulators were in charge.

QCA commissioned researchers to investigate three issues: what students would need to become scientifically literate citizens, what should constitute a curriculum to meet those needs and how students’ learning in a new and different science curriculum could be assessed (QCA 2006).

The first study involved consulting groups with an interest in school science education about the features of the proposed curriculum. The consultation was carried out by a group of researchers from the Centre for Studies in Science and Mathematics Education, University of Leeds (Leach 2002). Secondary science teachers in focus groups were presented with an outline of a curriculum, broadly in line with the thinking in the *Beyond 200*0 report, with these features:

- It views pupils as potential users and consumers of science, rather than as potential producers of scientific knowledge.
- It aims to give pupils a sense of the cultural significance of science.
- It covers less of the traditional conceptual content of science, allowing time to cover key areas in significantly more depth.
- It gives more attention to the ways in which science works, emphasising ‘how we know what we know’.
- It introduces scientific disciplines that predict risk, such as epidemiology, and reduces the amount of time spent on the ‘traditional’ school science disciplines of physics, chemistry and biology.

The findings from this study suggested that secondary science teachers were generally dissatisfied with the existing curriculum and supportive of change; however, they did not share a common vision of what a science curriculum for all students might look like. The researchers concluded that any future attempts to change the focus of the science curriculum would have to take seriously the need for such a shared vision to emerge within the science teaching profession if the changes were to be successful. Consulting more widely, the study identified many ‘critical voices’ in relation to the meaning and feasibility of the goals of scientific literacy.

The second study was carried out by researchers from King’s College London and the University of Southampton (Osborne and Ratcliffe 2002). The aim was to explore appropriate methods of assessment for a new curriculum featuring ideas and evidence, in a curriculum intended to develop understanding of the nature and limitations of scientific endeavour, through historical and contemporary contexts. The challenge was to find assessment tasks which would encourage teachers to explore not only which scientific ideas are believed but why they are believed. The researchers were looking for assessment items covering the relationships between the claims, data and warrants for trust in scientific ideas.

The research team studied examples of assessment in this field from across the world. In their interim report the researchers stated that it was their general impression that, internationally, the assessment of the nature and processes of science was an underdeveloped field. They reported that they had found relatively few sources that had created a significant body of items for testing understanding of the nature of science, the analysis and interpretation of data and the processes of science. Nevertheless they were able to use their findings to assemble four written tests and four teacher-assessment tasks that were tried out in schools.

From the analysis of the test results, the research team concluded that reliable and valid items for testing pupils' understanding of the processes and practices of science in contemporary or historic contexts could be developed. The researchers argued that many of the items and the teacher-assessment tasks offered authentic contexts for assessment. However, they pointed out that teachers considered the amount of reading and the language level to be off-putting, but that such comments reflected a tension between what was currently being taught and the comparative 'novelty' of the content and emphases of the items being trialled. The researchers identified unresolved issues and areas in which further work was needed.

The third study was carried out by the University of York Science Education Group (UYSEG) in collaboration with the Association for Science Education and the Nuffield Curriculum Centre. The aim was to devise a curriculum model that would meet the two overarching purposes of science education identified in the *Beyond 2000* report: the development of scientific literacy for all and preparation for post-compulsory science study for some.

The curriculum model proposed that all students would complete a 'core' course (UYSEG 2001). This course would provide 'a broad, qualitative grasp of the major science explanations' and also include insights into the nature of science and its relation to social and ethical issues. In addition, most students would also opt for one of two additional science courses offering either traditional science content or a focus on the applications of science within everyday and work-related contexts (*Twenty First Century Science* project team 2003).

QCA acted on the recommendations of the third study and commissioned the OCR awarding organisation[21] to produce a suite of pilot GCSE qualifications to match the curriculum model. QCA used the findings of the second project to inform

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[21] There are three awarding organisations in England responsible for GCSE and A-level specifications (syllabuses) and examinations. The three were formed by the merger of a number of previous examination boards. The three are AQA, Edexcel and OCR. Specifications and examinations have to conform with national criteria that were formerly produced by QCA but are now controlled by a regulator called Ofqual.

the national testing of science for younger pupils, but there was a lack of thorough development work to devise appropriate methods of assessment of ideas-about-science for GCSE courses. The recommendations of the first study were not followed up (Ryder and Banner 2011).

The University of York Science Education Group and the Nuffield Curriculum Centre set up *Twenty First Century Science* as a large-scale curriculum development project to provide the teaching resources and support needed by the schools taking part in the trials of the new GCSE courses commissioned by QCA and run by OCR[22] (Millar 2006). The project was funded by grants from three charitable foundations including the Nuffield Foundation whose trustees supported the recommendations of the *Beyond 2000* report.

Development of the resources began in 2002 in preparation for a pilot that ran in nearly 80 schools from 2003. QCA carried out early, small-scale evaluation studies of the pilot and concluded, well before the end of the pilot, that the findings were sufficiently positive to justify reworking the national curriculum and GCSE science criteria broadly in line with the model being trialled (QCA 2005). A larger-scale evaluation of the pilot was commissioned by the charitable trusts funding the development project, but the findings were published too late to influence the national developments (Burden et al. 2007).

63.12 A New National Curriculum Featuring ‘How Science Works’

Drawing on all the work done since 2000, the QCA introduced a new version of the national curriculum in 2004.[23] This was divided into two major strands: ‘knowledge and understanding’ and ‘how science works’. The curriculum model was a response to the notion that science education should not only communicate a body of knowledge but also convey an understanding of how that knowledge has been, and continues to be, developed. This required that the curriculum place greater emphasis on the nature of science and the way scientists and the scientific community as a whole operate.

There were four main sections of the ‘how science works’ strand (Toplis 2011):

- Data, evidence, theories and explanations
- Practical and inquiry skills
- Communication skills
- Applications and implications of science

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[22] The latest version of the Twenty First Century Science GCSE Science specification can be downloaded from the OCR website at http://www.ocr.org.uk/qualifications/type/gcse_2011/tfcs/ (accessed November 2011).

[23] This version of the national curriculum for students aged 14–16 will probably continue to apply until 2014. It is available from the Department for Education website: http://www.education.gov.uk/schools/teachingandlearning/curriculum/secondary/b00198831/science/ks4/programme (accessed June 2012).

Table 63.2 How science works in AQA and OCR-A specifications

Concepts of evidence in AQA specifications (the thinking behind the doing)	Ideas-about-science in Twenty First Century Science
Observation as a stimulus to investigation	Data and their limitations
Designing an investigation	Correlation and cause
Making measurements	Developing explanations
Presenting data	The scientific community
Using data to draw conclusions	Risk
Societal aspects of scientific evidence	Making decisions about science and technology
Limitations of scientific evidence	

However, the national curriculum has never provided enough information to allow regulators to set a detailed framework for GCSE specifications. To give awarding organisations more specific guidance, the curriculum authorities produce GCSE subject criteria. The new criteria published for the 2004 curriculum offered considerable flexibility with the result that the awarding organisations came up with very different interpretations of ‘how science works’. Two sets of specifications were based on fully developed rationales derived from research and scholarship. These are compared in Table 63.2. Most of the 600,000 or so students that take GCSE Science each year follow one or other of these popular courses.

AQA[24] adopted a rationale for teaching about the methods of science based on the work of Gott and Roberts (2008) at Durham University.[25] This approach focussed on the procedural understanding and understanding of concepts of evidence that are needed to carry out and interpret science investigations.

The OCR Twenty First Century Science specifications[26] were updated from the pilot versions and used the rationale for teaching ideas about science that informed the *Beyond 2000* report based on the work of Robin Millar and his collaborators at the universities of York, King’s College London, Southampton and Leeds. The approach in the core science specification was designed to develop the scientific literacy of all young people. The thinking was that a course based on this rationale would help to develop the knowledge and understanding that are most useful in interpreting and evaluating the sorts of science-based information and claims that everyone encounters in their adult and working lives (Millar 2013).

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[24] Details of AQA GCSE Science specifications are available from the website of the awarding organisation: http://web.aqa.org.uk/qual/newgcses/science.php (accessed June 2012).

[25] See the Research Report: Background to Published Papers by Richard Gott and Ros Roberts at http://www.dur.ac.uk/education/research/current_research/maths/msm/understanding_scientific_evidence/ (accessed June 2012).

[26] The Nuffield Foundation website provides details of the Twenty First Century Science courses (rationale, published resources, assessment methods and support for teachers). See http://www.nuffieldfoundation.org/twenty-first-century-science (accessed March 2012).

63.13 Assessing 'How Science Works'

At that time there was no significant investment in developing appropriate methods of assessing 'how science works' in written examination papers. Bringing in this new emphasis to the curriculum made fully explicit ideas that had previously been implicit. There was no accumulated expertise in assessing the ideas, which meant that the examiners for all the awarding organisations had much to learn. Consequently, in the early years the assessments had unsatisfactory features as shown by a SCORE[27] (2009) report on GCSE examinations.

The problems with the assessment of 'how science works' were investigated in more detail by research commissioned by SCORE in 2010. The research team reported that they had found wide variation in the breadth and depth of the treatment in the different GCSE course specifications and examinations (Hunt 2010).

One clear conclusion was that the societal (STS) aspects of this area of the curriculum were being given very substantial, but rather trivial, emphasis compared with the treatment of ideas related to the methods of science and the nature of scientific explanations.

The consequence was that the assessment practices were not fit for purpose and so did not have the confidence and support of the community including teachers. Test items in written examinations failed to show that they assessed knowledge and understanding that every young person needs. As a result many people failed to appreciate that the teaching of 'how science works' could be based on rigorous concepts and challenging learning goals.

The findings of SCORE and others led to a further revision of GCSE specifications and assessments with the aim of bringing greater clarity and consistency to the assessment of ideas related to the methods and nature of science.

63.14 Argumentation and the IDEAS Project

The introduction of 'how science works' emphasises the importance of educating students about how we know and why we see science as a distinctive and valuable way of knowing. This means that students need to explore reasons why accepted theories have become established and why alternative ideas are thought to be wrong (Simon 2011).

Shirley Simon, with Jonathan Osborne and Sibel Erduran at King's College London decided to study the implications of teaching science based on the view that what lies at the heart of science is the commitment to evidence as the rational basis for argument and justification. The group worked with teachers in a research project

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[27] SCORE is a partnership of organisations which aims to improve science education in UK schools and colleges. The organisations: Association for Science Education, Institute of Physics, Royal Society, Royal Society of Chemistry and the Society of Biology.

called *Enhancing the Quality of Argument in School Science* (Osborne et al. 2004a). Influenced by their findings, they then developed the publications of the IDEAS project (Osborne et al. 2004b).

The team produced the pack to support the professional development of teachers. They did so because they believed that, in presenting scientific ideas and their supporting evidence to school students, it was essential to consider the arguments for the scientific ideas and other competing theories. One reason for this was that the research evidence suggested that the opportunity to consider why the wrong idea is wrong is as important as understanding the justification for the scientific idea. A second reason was that engaging in argument provides students with a better insight into the nature of scientific enquiry and the work of scientists.

Activities in the pack explored what is meant by the term ‘argument’ in science and why it is a significant feature of science, bearing in mind that the everyday meaning of the word ‘argument’ is not the one that is being used in this context. Teachers were introduced to Ron Giere’s (1991) epistemological framework and asked to discuss its relevance to sciences ranging from cosmology and geology to biochemistry and physics.

The pack also introduced teachers to the ideas of the philosopher Stephen Toulmin (1958). Activities in the pack gave participants opportunities to use Toulmin’s model to analyse and construct scientific arguments. The arguments were mainly related to evidence and explanations. Debate about socioscientific issues was included but was not the main focus of the activities.

63.15 How Science Works in Post-16 Specialist A-Level Science Courses

Following the changes to the national curriculum, the QCA, added a section on ‘how science works’ to the national criteria for A-level sciences when they were revised for post-16, specialist science courses starting in 2008 (Ofqual republished annually). Section 63.7 of the criteria includes the requirement that science A-levels should enable students to appreciate the tentative nature of scientific knowledge, consider ethical issues in the treatment of humans, other organisms and the environment and appreciate the role of the scientific community in validating new knowledge and ensuring integrity.

A review of the new A-level specifications based on these criteria shows that the new section covering how science works has had a limited impact on most courses.[28] However, the Advancing Physics[29] specification is of particular interest because it has a coherent rationale for ‘how science works’ fully integrated into the course

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[28] This was found, for example, during an unpublished review of specifications carried out by one of the authors for SCORE in 2012.

[29] Information about the course, the published resources and the assessment can be found on this website: http://www.advancingphysics.org/ (accessed in June 2012).

design, content, assessable learning outcomes and scheme of assessment. This rationale covers relatively few ideas but in greater depth and provides a distinctive justification for the inclusion of 'how science works' in advanced courses. Students who follow this course are, for example, assessed on their ability to:

- Identify and discuss ways in which interplay between experimental evidence and theoretical predictions have led to changes in scientific understanding of the physical world
- Use computers to create and manipulate simple models of physical systems and to evaluate the strengths and weaknesses of the use of computer models in analysis of physical systems
- Identify and describe the nature and use of mathematical models
- Identify and describe changes in established scientific views with time

Some other advanced courses take a context-led approach which provides opportunities to feature case studies in the history of science. One example is Salters-Advanced Chemistry,[30] which uses aspects of the history of chemistry to illustrate conceptual and technological developments in some of the topics. Storylines in the course with a strong historical dimension include 'The polymer revolution', 'What's in a medicine' and 'Colour by design'.

Another context-led approach is Salters-Nuffield Advanced Biology.[31] This is a course that introduces students to ethical principles that enable them to analyse and discuss biological issues (Reiss 2008). Students learn about four ethical frameworks: rights and duties, utilitarianism, autonomy and virtue ethics. Implicit in the approach, as Michael Reiss explains, is the notion that one can be confident about the validity and worth of an ethical argument if three criteria are met (Reiss 1999). First, if the arguments that lead to the particular conclusion are convincingly supported by reason. Secondly, if the arguments are conducted within a well-established ethical framework. Thirdly, if a reasonable degree of consensus exists about the validity of the conclusions, arising from a process of genuine debate.

63.16 Teaching About the Nature of Science at A-Level

Research and development work to explore post-16 students' understanding of aspects of 'how science works' has been limited. However, starting in 1999, a team at the University of Leeds carried out a small-scale project, called *Teaching about*

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[30] Information about the course, the published resources and the assessment can be found on this website: http://www.york.ac.uk/org/seg/salters/chemistry/index.html (accessed in March 2012).

[31] Information about the course, the published resources and the assessment can be found on this website: http://www.nuffieldfoundation.org/salters-nuffield-advanced-biology (accessed in March 2012).

Science during which they designed teaching resources[32] to develop students' understandings about aspects of the nature of science in post-16 A-level science courses. They evaluated the impact of the resources and identified areas of knowledge and expertise that act as barriers to teachers in using the materials to promote student learning about the nature of science (Leach et al. 2003).

The focus of the project was on epistemological aspects of AS-/A-level syllabuses. The lessons were designed to address misconceptions which research had shown to be commonly held by students. Students have misconceptions about the nature of theoretical explanations in science. They tend to believe that theoretical models emerge directly from data and that all features of a theoretical model correspond directly to features in the real world. They often fail to recognise the conjectural and tentative nature of many scientific explanations and that scientific explanations are often expressed in terms of theoretical entities which are not 'there to be seen' in the data. Three lessons were designed to address these misconceptions: A *Electromagnetism,* B *Cell membranes* and C *Continental drift.*

Other misconceptions relate to the assessment of the quality of scientific data. Students tend to see examination of the quality of scientific evidence as simply a matter of making a judgement about whether the scientists involved had made any mistakes. They often fail to recognise the inherent uncertainty of measurements and have little idea of how scientists deal with this uncertainty. Few students use ideas about the validity and repeatability of evidence in evaluating its quality or recognise the significance of examining the spread of a set of data. Lesson D *Chemical data* and lesson E *Mobile phones* were designed to address these misconceptions.

A third set of misconceptions relate to the purposes of scientific investigations. Students tend to see scientific investigation as a process of careful description. For such students collecting a 'good' set of data is the end of the data interpretation process. They often fail to recognise that many investigations involve the testing of ideas. The need to interpret the data in terms of scientific ideas is not recognised. Lesson F *Purposes of Science* was designed to address these misconceptions.

The technical report on the project (Hind et al. 2001) concluded that overall the interventions provided by the lessons had been successful in broadening the profile of views about the nature of science which some of the students in the sample drew upon in response to a specific context. However, there were also a number of students for whom these single interventions had little effect judging by the evidence of their evaluative probes. Furthermore, observations and interviews with teachers highlighted the difficulties for teachers in teaching about the nature of science, something that for many teachers is unfamiliar.

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[32] The lessons developed and trialled by the Teaching about Science project can be downloaded from the Nuffield Foundation website: http://www.nuffieldfoundation.org/teaching-about-science (accessed in March 2012).

63.17 An Alternative Approach to Teaching the History and Philosophy of Science

63.17.1 Origins of the Perspectives on Science Course

The Perspectives on Science course has its origins in conversations about the need for a qualification which would give post-16 UK students an opportunity to explore and develop their own ideas concerning topics related to the history and philosophy of science.[33] The course development process was initiated by Becky Parker, John Taylor (both science teachers) and Elizabeth Swinbank from the University of York Science Education Group. The rationale for developing the qualification was that students enjoy discussions in which issues relating to the epistemology and metaphysics of science are raised but that there is often little scope for exploring these during science lessons due to lack of time (Taylor 2012). Moreover, it was felt that providing students with an opportunity to explore 'the human face of science' by a study of the history of science would help them to develop a more realistic understanding of the nature of science and also help to break down the divide between 'scientific' and 'humanities' styles of thinking. It was felt too that study of the history and philosophy of science had value in helping to develop students' skills in critical thinking (Swinbank and Taylor 2007).

63.17.2 The Perspectives *Approach to Teaching the History of Science*

In certain respects, the *Perspectives on Science* course was similar in aim and design to the *Science for Public Understanding* course described above. Both developments exploited the opportunity afforded by changes in the post-16 national curriculum, specifically the introduction of the 'AS-level'. Both were developed in a context in which there was growing emphasis on the importance of developing the scientific literacy of students (Millar and Osborne 1998) and both therefore aimed to help students to develop their ideas about science.

However, the *Perspectives on Science* approach was distinctive in a number of respects. Firstly, it was not developed as a science qualification but as a programme in the history and philosophy of science. Whilst the course materials drew on scientific cases studies, the programme of study was designed to teach students how to apply the methods of historical and philosophical analysis to scientific material, rather than to teach them more science. Moreover, the qualification aimed to give a central place to pedagogical techniques, such as classroom discussion and debate,

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[33] See Bycroft (2010) for further discussion of the development of the course.

more commonly associated with humanities subjects, and to teach students how to produce extended research dissertations.

Secondly, the course developers deliberately chose a different approach to the question of how ideas about science should be taught than that embodied in the *Science for Public Understanding* course. Whilst the *Science for Public Understanding* course developers selected a list of ideas about science which were taught as part of the prescribed course content, the *Perspectives on Science* chose not to use any such list. The course was designed specifically to allow students the opportunity to develop their own ideas. There was in fact no prescribed course content. Instead, the programme of study was constructed in such as way as to teach students the skills they needed to begin thinking for themselves about historical and philosophical questions relating to science. The aim of the course was to teach students *how* to think in these ways, not *what* to think. The course materials did use a series of case studies, in which issues from the history and philosophy of science were introduced, but these were selected because they were felt to provide good contexts for the skills of historical and philosophical research and analysis, rather than because they were thought to contain essential subject knowledge.[34]

A third distinctive feature of the *Perspectives on Science* was the mode of assessment. The course was unique amongst post-16 UK AS-level qualifications in that assessment was entirely by means of a student research project and oral presentation and not by means of a written exam. This mode of assessment was felt to be the most suitable, given that the aim of the course was to encourage students to develop their own ideas through processes of research and argumentative discussion. Students were allowed to make a free choice of topic for their dissertation, although guidelines existed to lead them towards research questions which were well focussed, with links to research literature and with scope for analytic thought and argumentative engagement.

As Edgar Jenkins (1994) points out, the common feature of most attempts to include insights from the history and philosophy of science in school curricula is that the teaching is assumed to be essentially supportive of the goals of science education itself; it is not expected to challenge its traditional purposes. This is where *Perspectives on Science* opened up a new line of development, allowing teachers and students to respond directly, and in its own terms, to scholarship in the history and philosophy of science. One student, for example, chose to write a project in which she argued that witch-hunting was a scientific activity (witch-hunters based their conclusions on evidence and carried out trials). The historical component of her project was informed by documentary research involving a visit to a county records office to read records of witch trials, and, philosophically, she drew on Feyerabend's radical critique of the notion of scientific method. Another student chose to write about the extent to which the problem of the incommensurability of rival paradigms undermines the idea of objective progress in science.

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[34] The student and teacher guides for the course provide further details (Perspectives Project Team 2007a, b).

These examples illustrate the way in which students had a degree of freedom which was unusual in courses which are part of a national qualification framework to engage with scholarly arguments and challenge conventional conceptions of the nature of science.[35]

The point made in Ziman (1994) about the tendency of courses in the history and philosophy of science to endorse oversimplified, Whiggish interpretations of the history of science was addressed by the use of carefully constructed case studies which embody good historiographical practices, including contextualization of scientific developments, exploration of rival conceptual schemes and the exploration of historically complex narratives, such as that of the developing understanding of oxygen, or the recent controversy about cold fusion, which act to counter the idea that the history of science is a tale of steady progress towards an agreed-upon truth.[36] Students addressing projects with historical dimensions were expected to apply these techniques in writing literature reviews, which showed critical awareness of issues such as source reliability and objectivity, and manifested awareness of the wider context within which the developments they discuss took place. The successful application of these techniques of historical analysis formed one strand in the assessment criteria for the dissertation.

63.17.3 The **Perspectives** *Approach to Teaching the Philosophy of Science*

The approach to the philosophy of science was determined by the fact that the aim of the course was to equip students with the knowledge and skills to begin to develop their own philosophical ideas about topics related to science. This was achieved in the programme of study by using a sequence of lessons designed to help students develop skills in critical thinking and conceptual analysis. In most cases, the lessons involved little didactic instruction, although some teaching of common philosophical frameworks took place. Topic areas addressed include science and religion, the nature of scientific truth, genetics, animal welfare, medical ethics, the mind, artificial intelligence, free will and determinism, pseudoscience and the paranormal. Case

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[35] Examples such as these may reawaken the concern expressed – with tongue-in-cheek – by Brush (1974) about the risk that teaching students the history of science will have the damaging consequence of subverting a convergent realist interpretation. But as Brush himself concludes, it can be argued that helping students to develop a more realistic picture of how scientists behave will have ‘redeeming social significance’. As Matthews (1994/2014, p. 7) notes, HPS programmes can humanise the sciences, and there is evidence that this makes science programmes more attractive to students, particularly girls. It was this thought which informed the approach of the *Perspectives on Science* course. In this connection it is worth pointing out that both of the projects exemplified above were written by girls, one of whom chose to change from studying History at Cambridge to studying History and Philosophy of Science because she had found it such an enjoyable subject.

[36] The history of science section of the *Perspectives on Science* course was written by Peter Ellis, with John Cartwright contributing a section on the discovery of oxygen.

study material from these subject areas was used as a stimulus for classroom discussion and debate, the aim of these discussions being to engage student interest, as well as to help strengthen students' ability to engage in reasoned argument. To this end, teaching about argument structure was integrated into the programme of discussion of philosophical topics.

Inevitably, a short course in the philosophy of science can only provide an introduction to a select number of the central debates in the field. The written dissertation provided the context for greater depth of study of a specific research question with an historical and/or philosophical dimension. So, for example, a student who found discussion of philosophical questions linked to genetics particularly interesting might choose to study the question of whether autism has a genetic cause, and as part of this, to explore in greater depth the way the concept of causation functions in such a setting.

63.17.4 Teaching and Teachers

In 2007/2008, a team from the Institute of Education at the University of London carried out a research study of *Perspectives on Science* (Levinson et al. 2008, 2012). The researchers noted that discussion topics mostly tended to involve ethical questions, which tend to be very effective in helping students engage in discussion as the substantive knowledge needed is quite accessible. They noted that diversity, passion and extreme viewpoints amongst students can be productively harnessed. They also noted that there were far fewer projects which focussed on the history of science (a point further discussed in Bycroft 2010) and urged that teachers should try to address more challenging philosophical and historical issues as students' discussion skills develop.

The research study of the *Perspectives on* Science course echoed others (Monk and Osborne 1997) in noting teachers' problematic lack of knowledge of the philosophy of science. This is an area which teachers who felt that they would like further training identified as the one in which they were most in need of additional support.

63.17.5 Implications for Science Education

The *Perspectives on Science* course ran as an AS pilot between 2004 and 2008. In the final pilot year, 31 UK schools taught the course. As a small-scale programme, the question arises as to whether it constitutes another instance of the observed failure of programmes in the history and philosophy of science to contribute to mainstream science education (Monk and Osborne 1997).

Despite its small size, the *Perspectives on Science* course has some claim to have had an influence on wider educational developments and to have the potential to contribute to mainstream science education. This is mainly because of the part it has played in shaping the *Extended Project Qualification*, which was launched nationally in 2008 and which by 2011 attracted almost 25,000 student entries. This qualification provides post-16 students with an opportunity to carry out a major research project on a topic of their own choice. The *Perspectives on Science* course served as a model for the dissertation unit of the *Extended Project* offered by the Edexcel awarding body. A number of elements of the *Extended Project* dissertation model, namely, an emphasis on the writing of an historically focussed literature review, with critical evaluation of source objectivity and reliability and consideration of context, use of philosophical reasoning in addressing issues which are not susceptible to empirical resolution and exploration of ethical issues arising from scientific and technological developments, derived directly from the approach piloted in the *Perspectives on Science* course.

The *Extended Project* also offers a Field Study/Investigation unit, and this unit provides an opportunity for in-depth scientific investigation, with the construction of hypotheses, data collection and analysis which involves exploration of the extent to which data supports hypotheses. Significantly for the purposes of teachers wishing to integrate elements of the history and philosophy of science within their science teaching, *Extended Project* investigations also require students to show awareness of the wider context of their research, and this can lead them in the direction of historical study or exploration of social, economic or ethical issues related to their investigation. So, for example, one student carried out an investigation with the title ‘Global warming: Anthropogenic or Astronomical’, in which he researched the recent history of one aspect of debate about the causes of climate change then went on to experimentally test the hypothesis that cloud cover could be affected by cosmic ray flux. Another student carried out an investigation under the title ‘What is the most effective method of producing aspirin and is it justifiably described as a ‘wonder drug’?’, in which she researched the history of the development of aspirin, explored the controversy about who first synthesised acetylsalicylic acid, examined the way aspirin is presented in the media, discussed problems of access to aspirin in less economically developed countries and then carried out a laboratory comparison of the yield of two different synthetic pathways to a precursor of aspirin.

Currently, the number of students who are writing *Extended Projects* in which scientific questions are explored in this contextual manner, with consideration of ethical, historical and philosophical aspects, or with links to empirical work, is not large. But it is significant that this work is beginning to take place as part of mainstream science education, at least at post-16 stage. Monk and Osborne (1997) noted that science teachers will begin to engage with the history and philosophy of science only insofar as it can be shown that this engagement contributes to their students’ examinable knowledge and skills. As a result of the development of the *Extended Project,* informed by the *Perspectives on Science* course, there exists a national qualification, the assessment criteria of which have been shaped to be conducive to gaining a deeper understanding of scientific topics, as well as others, by means of historical and philosophical enquiry.

63.18 Conclusion

Despite 50 years of exploration and over 20 years of the national curriculum's treatment of the history of science and the nature of science, there is still no consensus in England about the ideas-about-science that should feature in the curriculum. This is shown, for example, by the public debate that followed the introduction of 'how science works' into the curriculum (Perks 2006). Over the period covered by this chapter, it is notable how long it has taken to bring about systemic change.

Despite the slow pace of change, much has been learned about the conditions needed to introduce teaching about the history and nature of science into mainstream science education. One lesson is that it is important that new courses lead to recognised qualifications even during the pioneering phase. It is also important that methods of assessment are devised that reward teaching and learning in line with new aims. A significant reason why it has taken so long to embed teaching about the nature of science into the everyday thinking and practice of science teachers is that it has proved difficult to specify the intended learning outcomes in language that is widely understood and accepted. This has the consequence that it has been difficult to devise assessment items for examinations that encourage good practice in schools.

Another barrier to change has been that teaching about the nature of science can be a formidable challenge to those teachers whose own education and training has not helped them to reflect on the history and philosophy of science themselves. At the very least, dissemination of ideas and teaching methods beyond an initial group of enthusiasts depends on the production of high-quality resources in print and other media. In England the production of such resources, especially in the early stages, when their commercial value was in doubt, has been heavily dependent on support from number of charitable foundations. Opportunities for professional development are important too, but they have generally not been provided on a large enough scale to change the general culture of science teaching.

The English experience shows that it is crucial that the course content and teaching methods are rooted in the practical realities of school classrooms. All the early developments described in this chapter grew out of the interests of teachers. Subsequently some of these teachers moved into curriculum development and into universities, without losing interest in the field. Thus grew up a strong and enduring partnership between practitioners in schools and academics in higher education. The footnotes and bibliography for this chapter reflect the fruitfulness of this collaborative approach with their mixture of references to a great variety of tried-and-tested resources as well as references to research papers and scholarly articles.

An extraordinary feature of the science curriculum in England since the introduction of the first national curriculum in 1989 has been the rapidity of change. New versions of the science curriculum for students aged 14–16 were published in 1989, 1991, 1995, 2000 and 2004. The curriculum for those aged 11–14 was also revised in 2006. Further change is underway following the election of a new government in 2010. This government has abolished the curriculum authority, QCA, so that changes to the curriculum are now under the direct oversight of ministers. This is a complete reversal of the situation in the 1960s when politicians kept out of 'the secret garden'[37] of the curriculum.

In its first statements about the new science curriculum, the Department for Education[38] has stated that one of the aims should be that students develop their understanding of the nature, processes and methods of science. However, the approach is likely to change and the term 'how science works' will almost certainly disappear from official documents. An early draft of the curriculum suggests that in the future students should develop their understanding of these aspects of science through practical activity.

The development of many of the initiatives discussed here derived from the desire to create curriculum space for discussions of questions about the history and philosophy of science to be taken further. The *Perspectives on Science* approach pioneered the use of such discussions as a catalyst for independent student enquiry and project work. It has recently been argued (Taylor 2012) that teaching itself should be seen as a philosophical activity and that, to counter the tendency of assessment to determine pedagogy, teachers should focus more on equipping students to think critically and enquire independently in all areas of study. It has also been argued that conceptual understanding, which is fundamental to all learning, presupposes a grasp of the historical and philosophical matrix within which scientific knowledge exists (Blackburn 2010). If these arguments can be sustained, in the teeth of an educational culture dominated by the pressures of high-stakes assessment and accountability measures, it may yet come to be recognised that ideas emerging from the history and philosophy of science teaching community can be beneficially applied to mainstream science education.

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[37] The term 'secret garden' was popularised in connection with a speech by the Labour Prime Minister Jim Callaghan in 1976. He started a debate that led in time to the national curriculum. He argued that it should not be teachers alone that determine the curriculum but that parents, learned and professional bodies, representatives of higher education and both sides of industry, together with the government, all have an important part to play in formulating and expressing the purposes of education and standards.

[38] The latest information about the national curriculum is published on the Department for Education website: http://www.education.gov.uk/schools/teachingandlearning/curriculum/nationalcurriculum

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Chapter 64
Incorporation of HPS/NOS Content in School and Teacher Education Programmes in Europe

Liborio Dibattista and Francesca Morgese

64.1 Government Policies and Recommendations for the Teaching of Science with the Historical-Critical Approach

64.1.1 Europe

The crisis of scientific vocations has been a pressing subject in the agenda of developed countries, and the relationship between the *crisis of scientific education and social, political and economic development* has been widely acknowledged. The question had already arisen in the White Paper *Teaching and Learning: Towards the Learning Society* (European Commission 1995): facing rapid changes, the widening of the exchanges to a world dimension, the rise of the information society and rapid progress in science and technology. There was a *paradoxical* reaction by European citizens that would see as a *threat* and with *irrational fear* the scientific and technological innovations. These should instead have been considered as instruments for the acquisition of new competences and competitiveness on the job market.

The 1995 European Commission document hoped for the involvement of initiatives and actions for the diffusion of culture and scientific and technological information that might emphasise the value of science and technology for the progress of humanity. Promoting *general culture* and *scientific culture* in this case was meant as a support for the society of knowledge: 'Clearly this does not mean turning everyone into a scientific expert but enabling them to fulfil an enlightened role in making choices which affect their environment and to understand in broad terms the social implications of debate between experts. There is similarly a need to make everyone

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capable of making considered decisions as consumers' (p. 11). Traditional science teaching, aiming at the mastery of a strictly logic order, of the deductive system, of abstract notions among which mathematics dominate, seems to paralyse and to make a passive subject of the learner, suffocating his imagination.

The finger was pointed at the tendency of teaching to 'present[ing] the world […] as a completed construction', and member states were invited to promote initiatives for the introduction of the history of science and technology as part of science education.

The debate on education *tout court*, and particularly on scientific and technological education, was dealt with later by the commissions of a number of European Councils. The one in Lisbon in 2000 (European Council Lisbon 2000) identified for the decade 2000–2010 the goal of making European economy *knowledge based*: 'the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion', confirming the relationship between education, training/growth and European economic development. After Lisbon, the new 'noticeable' issue has been to promote the *candidateship of scientific and technical studies*, one of the objectives discussed in the European Council of Stockholm 2001 where it was asserted that European competitiveness needs a number of mathematics and science experts and it is dangerous that these studies are deserted by European youths, who show a negative attitude towards them and an inferior learning to expectations (European Council Stockholm 2001).

The need to *attract more students to technical and scientific studies* has become from that moment one of the *leitmotif* of the European documents: in Barcelona (European Council Barcelona 2002), for example, they proposed a 'general renewal of pedagogy' and the use of 'development strategies aiming at the performance of schools in encouraging pupils to study natural science, technology and mathematics and in teaching these subjects'. In Brussels (European Council Brussels 2003), the objective to be achieved was an increase of 15 % in the number of graduates in mathematics, science and technology. Subsequent European Councils would monitor and record the implementation of the Lisbon strategy and the achievement of the objectives proposed in the preceding years.

In this panorama are included the huge survey campaigns on the level of learning of European students, to which Italy too has been participating for at least 30 years (INVALSI 2008).

In short, these documents strongly stressed *education/economic development* and the need to for scientific culture to *renew its methods* and *teaching practices.* On closer look, however, there is not a precise indication with regard to the strategies to follow in order to achieve such renewal.

The first document to express more practical insight on the subject was the 2004 report released by the European Commission, *Europe needs more scientists!* (European Commission 2004), a series of recommendations aimed at increasing European human resources in the fields of science and technology. For the first time, a finger is pointed extremely clearly at the 'perception' of science that students form during their school years and which seems to be one of the most significant reasons for young people's difficulty in imagining themselves working in the future in a scientific career. School, by continuing to insist on 'counter-intuitive concepts and abstract ideas with no relevance to their daily lives', continues to immerse students in a context void of any real and deep understanding of science. Member states are invited to enrich their science curricula with wide-ranging interdisciplinary relationships between science, technology and other disciplines, with historical considerations which are neither stereotyped nor anecdotal and with wide-ranging and significant reflections on the nature of science (p. 138).

The 2005 survey called *Special Eurobarometer: Europeans, Science and Technology* had pointed out that 50 % of the European citizens interviewed agreed with the statement: 'science classes at school are not sufficiently appealing' (European Commission 2005, p. 99, 102), so it is the way science is taught in schools that turns off interest towards scientific subjects. The survey devoted a special section to the analysis of *scientific studies and the mobilisation of young people* to monitor European citizens' awareness about the role of science in society and to understand the causes for the loss of interest in scientific studies. What the survey showed was a *lack of understanding* of scientific and technological matters and a general feeling of *distance* from such issues.

Similar conclusions emerge from a survey made in 2006 (OECD 2006; European Commission 2006) on the evolution of young people's *interest* in science and technology: once again, formal scientific education is taken as the cause for the lack of natural curiosity towards science, this being even more serious since 'student choices are mostly determined by their image of S&T professions, the content of S&T *curricula* and the quality of teaching'.

These discussions and statements on scientific education have produced many of the research projects and teaching activities that will be illustrated in the second part of this chapter, one of which will be the description of the ROSE project.

The international[1] comparative project ROSE (the Relevance of Science Education) collected and analysed data on the factors that influence young people's perception of science and technology in scholastic and extra-scholastic contexts and reasons for the choices students make about whether or not they continue to study science. The target population is students towards the end of secondary school (age 15) and the research instrument is a questionnaire. The objective of ROSE is to collect enough information to develop proposals that will affect policy decisions in terms of scholastic curricula, reduce the extent of differences between the actual science and technology curriculum and that which the students would like to learn about and reinforce the relevance, attractiveness and quality of S&T education (Schreiner and Sjøberg 2004).

The reports of numerous countries which participated in the project[2] and a general summary which identifies the main results of the project are currently available (Sjøberg and Schreiner 2010). These reports show widespread interest on

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[1] About 40 countries have taken part or are taking part in ROSE. http://roseproject.no/.

[2] http://roseproject.no/publications/english-pub.html; http://roseproject.no/publications/other languages.html. For Italy, see Neresini et al. (2010).

the part of 15-year-olds in the subjects of science and technology, especially for those issues with more easily perceivable links to daily life and future work and professional possibilities. At the same time, knowledge of the importance of science and technology for society seems to be widespread among youth. However, the judgment of the relevance and attractiveness of the scientific disciplines studied at school[3] is more negative in the more highly developed nations than it is in those with a lower (HDI).[4]

Generally, in European countries the scientific subjects studied at school are seen to be important but difficult to understand, and this perception deters students from imagining themselves working in scientific professions in the future: '[…] school science fails in many ways' from the inability to involve students to the inability to arouse their curiosity, from shortcomings in making occupational possibilities perceivable to shortcomings in helping students to appreciate nature (Sjøberg and Schreiner 2010, p. 11). Additionally, it can be seen that students give a low rating to the interest of the contents present in texts and in the curricula. Low to average approval was found for knowledge about famous scientists and their lives, while high values were found for knowledge of the applicative 'context' of science and technology. An important result of the project is that 'there seems to be a need to 'humanize' school science, to show that science is part of history and culture' (Sjøberg and Schreiner 2010, p. 30).

A key document in the field is the so-called Rocard report (European Commission 2007) which finds new strategies to be implemented in teaching through the identification and promotion of *inquiry-based science education* (IBSE) and *problem-based learning* (PBL). This document promotes non-rote teaching based on abstract information and a teaching model based on the *processes of science* and on how it is practised, on concepts *transmitted through concrete experience*, on rich laboratory work, but most of all, an experience in which *learning proceeds through problem-solving*.

Since *problem-solving* implies the need to gather information, to identify the possible solutions, to evaluate in a critical way all the alternatives and show the conclusions, it would allow the students to engage in *active learning*, through the *building* of their own scientific knowledge. Teaching should rely on *concrete examples* as a way of providing access to understanding of the science.

Therefore, school being the most appropriate educational institution for providing training in scientific culture and career counselling, we reckon it is the place where these initiatives should be carried out.

We must clarify that the European documents have just an advisory value for member states and do not have compulsory effects on educational policies.

A detailed report prepared by the Eurydice European Unit on behalf of the Directorate-General for Education and Culture della European Commission (Eurydice 2011) contains a comparative investigation of regulations and official

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[3] Sixteen questions in the ROSE questionnaire focused on the assessment of this area (*My science classes*).

[4] Human Development Index.

recommendations on the subject of science teaching in Europe. Significantly, the title of executive summary is ‘Countries support many individual programmes, but overall strategies are rare’. In fact:

> Few European countries have developed a broad strategic framework to raise the profile of science in education and wider society. However, a wide range of initiatives have been implemented in many countries. The impact of these various activities is nevertheless difficult to measure … Most European countries recommend that science should be taught in context. Usually this involves teaching science in relation to contemporary societal issues … The more abstract issues relating to scientific method, the ‘nature of science’ or the production of scientific knowledge are more often linked to the curricula for separate science subjects which are usually taught in the later school years in most European countries. (Eurydice 2011, p. 9)

Moreover,

> Context-based science teaching emphasises the philosophical, historical or societal aspects of science and technology, as well as connecting scientific understanding with students’ everyday experiences. This approach is considered by some researchers to increase students’ motivation to engage in scientific studies, and possibly lead to improved scientific achievement and increased uptake. The science-technology-society approach requires science to be embedded into its social and cultural context. From a sociological perspective, this includes examining and questioning the values implicit in scientific practices and knowledge, looking at the social conditions as well as the consequences of scientific knowledge and its changes, and studying the structure and process of scientific activity. From a historical perspective, changes in the development of science and scientific ideas are studied. From a philosophical perspective, context-based science teaching raises questions regarding the nature of scientific inquiry and evaluates the grounds of its validity. It also recognises science as a ‘human endeavour’ where imagination and creativity play a role.
>
> Embedding science into its social/cultural context is considered important when teaching because the development of scientific knowledge may be viewed as a social practice which is dependent on the political, social, historical and cultural realities of the time. The process involves examining/questioning the values implicit in scientific practices and knowledge, looking at the social conditions as well as the consequences of scientific knowledge and its changes, and also studying the structure and process of scientific activity. At primary level, this approach is recommended in approximately half of European education systems. At lower secondary level, embedding science into its social and cultural context is suggested in 27 educational systems. The history of science is recommended in less than half of European education systems at primary level. At lower secondary level, the history of human thought about the natural world (from its beginnings in prehistoric times to the present) is suggested in more than half the European countries. The least common contextual dimension in science teaching at ISCED[5] 1 and 2 is the philosophy of science. Only about one third of European education systems at primary level and about a half of countries at lower secondary level suggest addressing questions regarding the nature or validity of scientific inquiry.(ibidem, pp. 65–66)

Figure 64.1 from the Eurydice report (reproduced after this paragraph) illustrates in which countries and at what level of education the *curriculum* for science teaching in primary and lower secondary education refers to science in context, either in terms of the history of science or contemporary societal issues or both.

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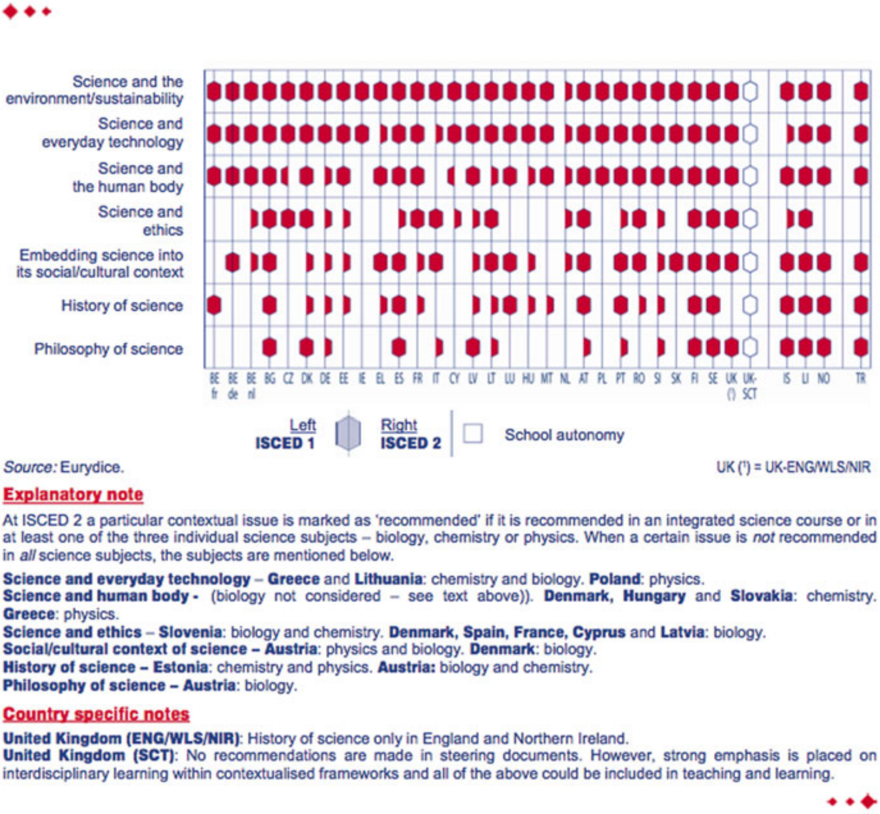
[5] ISCED: International Standard Classification of Education by UNESCO. (1) Primary education, (2) lower secondary, (3) upper secondary.



Source: Eurydice. UK (¹) = UK-ENG/WLS/NIR

Explanatory note

At ISCED 2 a particular contextual issue is marked as 'recommended' if it is recommended in an integrated science course or in at least one of the three individual science subjects – biology, chemistry or physics. When a certain issue is *not* recommended in *all* science subjects, the subjects are mentioned below.

Science and everyday technology – **Greece** and **Lithuania**: chemistry and biology. **Poland**: physics.
Science and human body - (biology not considered – see text above)). **Denmark, Hungary** and **Slovakia**: chemistry. **Greece**: physics.
Science and ethics – **Slovenia**: biology and chemistry. **Denmark, Spain, France, Cyprus** and **Latvia**: biology.
Social/cultural context of science – Austria: physics and biology. **Denmark**: biology.
History of science – Estonia: chemistry and physics. **Austria:** biology and chemistry.
Philosophy of science – Austria: biology.

Country specific notes

United Kingdom (ENG/WLS/NIR): History of science only in England and Northern Ireland.
United Kingdom (SCT): No recommendations are made in steering documents. However, strong emphasis is placed on interdisciplinary learning within contextualised frameworks and all of the above could be included in teaching and learning.

Fig. 64.1 Contextual issues to be addressed in science classes, as recommended in steering documents (ISCED 1 and 2), 2010/11

An update of this framework can be found at https://webgate.ec.europa.eu/fpfis/mwikis/eurydice/index.php?title=Home, where the 'Eurypedia (European Encyclopedia on National Educations Systems)' provides current information on national education systems of 38 European countries. The same report provides some news about improvements to science teacher education. In particular, it emphasises the relevance of improvement of teachers' views of the nature of science (NOS):

> In a professional development programme focusing on scientific modelling, teachers improved their views of NOS and inquiry as they expanded their definitions of science from a knowledge-based orientation to a process-based one. Furthermore, an informed understanding of the NOS can be enhanced by the use of meta-cognitive strategies (Abd-El-Khalick and Akerson 2009) and it seems that pre-service teachers who receive explicit instruction in the nature of science as a stand-alone topic are more able to apply their understanding of the nature of science appropriately to novel situations and issues than teachers learning within the context of a case such as for instance, climate change. (p. 104)

Many European countries are conducting programmes and projects for improving science teachers' skills. The survey SITEP (Survey on Initial Teacher Education

Programmes in Mathematics and Science) conducted by the Eurydice unit at the EACEA, which closed in late 2011, demonstrated no significant changes in teachers' approach. As a matter of fact, 'the most important competence addressed in teacher education is the knowledge and ability to teach the official mathematics/science curriculum'. However 'creating a rich spectrum of teaching situations, or applying various teaching techniques, is usually a part of a specific course in both generalist and specialist teacher education programmes. Applying collaborative or project-based learning and inquiry- or problem-based learning is frequently addressed in both types of teacher education programmes'.

The uniformity of the curricula in terms of competence, learning and, as a consequence, of certification and evaluation of the courses of study is something that Europe aspires to, as also shown by the publication of *The European Framework for Key Competencies*[6] (European Parliament 2006) and the *European Qualification Framework* – EQF[7] (European Parliament 2008) – which are two fundamental documents from the viewpoint of EU cooperation in education and lifelong learning. The European viewpoint is to promote collaboration between member states in view of the consolidation of a common European base of key skills and the facilitation of international exchanges and labour mobility. Nevertheless, we are still far from the attainment in Europe of uniformity in terms of science curricula at the level of primary and secondary instruction and also of teacher training.

An important European initiative which intends to enhance the range of quality of research in science education in Europe is ESERA (European Science Education Research Association),[8] formed at the European Conference on Research in Science Education held in Leeds, England, in April 1995. ESERA is an association of European science educators which aims to provide a forum for collaboration in science education research between European countries and to relate research to the policy and practice of science education in Europe. Through the organisation of conferences and the publication of reports, ESERA aims to highlight the major issues facing formal secondary science education, identify similarities and differences between countries and make a series of recommendations for improvement in key areas.

The latest report published, *Science Education in Europe: Critical Reflections* (Osborne and Dillon 2008), contains the conclusions of science educators from nine European countries. There are brief recommendations that analyse the current situation in science education in Europe and lay out the desired prospects for the future. Perhaps the most striking of these is the first recommendation which predicts the obligatory teaching of the nature of science (NOS) in secondary schools, while courses in individual scientific disciplines would become electives available to students who wish to prepare for careers in science. This is exactly the opposite of the current situation in European secondary schools. The reasoning behind this recommendation lies in the perception of standard science teaching as being both of

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[6] http://ec.europa.eu/education/lifelong-learning-policy/key_en.htm

[7] http://ec.europa.eu/education/lifelong-learning-policy/eqf_en.htm

[8] http://lsg.ucy.ac.cy/esera/index.html

little use and unappealing, based on the rote learning of abstract concepts, at a time when there is a need to provide students with basic knowledge of how science works and skills that will prepare them to address the problems of modern life and be informed citizens. On the other hand, the type of preprofessional training provided by a curriculum of single scientific disciplines ends up distancing youth from the prospect of undertaking a career in science.

The other recommendations underline aspects of science in context, the need for more female science teachers in the schools and the importance of early intervention since studies have demonstrated that student interest in science already begins to decline after age 14. Additionally, it is hoped that European governments will invest in the recruitment and support of a highly qualified teaching force, to be recognised both economically and socially, and realise the importance of modifying the current systems for evaluating abilities, knowledge and skills, which at this time focus too heavily on content performance tests such as the PISA. *Developing and extending the ways in which science is taught is essential for improving student engagement. Transforming teacher practice across the EU is a long-term project and will require significant and sustained investment in continuous professional development.* Finally, in the opinion of the report's authors, the best way to obtain this kind of science education for students lies in the study of the history of science and reflections on the epistemology and ethics of scientific enterprise.

In May 2011, the *Scientix Conference*, the conference of the community for science education in Europe, was held in Brussels. *Scientix* is a project of *European Schoolnet*, a network of 31 European Ministries of Education, supported by the European Commission. *Scientix* gathers and coordinates information on activities and results in the field of science instruction, including projects financed by the sixth and seventh European Union Framework Programmes, the initiatives of the *Lifelong Learning Programme* of the DGEC (*Directorate-General for Education and Culture*) and national initiatives. The key ideas set forward in Brussels highlighted how great the need is for scientific literacy in Europe, how important it is for educational policies to be coordinated with the needs of the workplace, how it is necessary to develop creative curricula and innovative teaching practices and how all of this is fundamentally related to the recognition (formal, intellectual, economic and political) of the key role played by teachers in European schools. John Holman, at that time director of the British *National Science Learning Centre*, mentioned in the welcome address, among other topics, the issue of how fundamental it is that teaching innovation be conveyed through curricula able to transmit, in addition to scientific contents, a clear idea of the *nature of science*, hence of the epistemology that structures scientific knowledge. If the magic formula is *inquiry-based science learning*, the questions and problems that produce 'science' as their answer are best learned by studying their history and philosophy. However, after this splendid inaugural declaration, epistemology and the history of science disappeared from the presentations at the Belgian conference.

In conclusion, in European policies on science education we can report a decrease in the emphasis given to the historical-philosophical approach during the last

15 years. As a matter of fact, in the final findings of the 1998 Strasbourg conference, conducted by Claude Debru, about the *History of Science and Technology in Education and Training in Europe*, it was expected that:

> all European students in science, technology or medicine should be strongly encouraged to attend a special course in the history of science, technology or medicine at least once during their studies. This teaching should be delivered at undergraduate level, as a element of general culture … Compulsory courses in history of science and technology should be part of the training received by science teachers at universities, so that they can convey a more dynamic view of science in their subsequent teaching at secondary schools…Students of history, philosophy and the social sciences should receive a specialized course in the history of science and technology at least once during their curriculum. The course should be compulsory in the training of future school teachers … The teaching of the history of science and technology should be systematically introduced in institutes devoted to the training of secondary-school teachers. (Debru 1998)

Eight years later, during the 2nd International Conference of the European Society for the History of Science, the round table discussion conducted by Claude Debru on the same argument showed no substantial changes; on the contrary:

> We should encourage the interest of DG (Directorate General) Research which lost interest in the Humanities in recent years after some signs of interest for master programmes … One relevant aspect lies in the intensified economic pressure on universities. This results in a challenge towards several academic disciplines that can have neither many students nor many third-party funds. Unfortunately, among these disciplines is also the history of science (P. Heering). (Kokowsky 2006)

Thirteen years later, sadly we cannot but repeat the account from Pietro Corsi in Strasbourg: ‘History of Science: Star of Research, Cinderella of Education’ (Corsi 2000).

64.1.2 Italy

The European guidelines have been acknowledged by the member states through initiatives, research and interventions that have contributed to bringing up the question of *scientific culture* in ministerial agendas and have engaged with public opinion, thus better defining the outlines and the content of the problem. In Italy, the fundamental question has been: *which factors are responsible for the falling interest in science and hamper the desire of the young in taking up a career in science?*

A common answer is that sciences per se do not arouse interest, since they are difficult and demanding disciplines (whether this is true or just a stereotype, prompted by an established cultural tradition, is the object of much research) and that a scientific degree, with the commitment and hard work employed in the process, does not necessarily turn into a well-paid and lasting profession.

However, these views do not coincide with those who work in science museums and science centres that are now quite widespread, including in Italy. They witness growing curiosity, interest and enthusiasm in the students who take part in educational visits as extra-school activities (Rodari 2008). This is an interest that seems to arise ‘only outside the classes and the departments’ (Crespi et al. 2005; Gouthier and Manzoli 2008, p. 143), and it has been predicted that it is rather ‘a positive involvement that will gradually fade away with the passing of the years’ (Cigada 2007).

These external contexts to the school world show that the problem lies in the *teaching methods*, in the *content*, in its *tools* and in the *methodologies* that are employed in the teaching process of scientific disciplines and also in the *image of science* that formal education conveys. Moreover, the formal organisation of school, compared with the non-formal approach of science centres, is an additional issue. The question seems to be the *lack of correspondence* between practised science and taught science in school. By *lack of correspondence* we mean to say that the way that science is taught and learnt leaves out the reconstruction of the problems that led scientists to carry out their research and the reasons that led them on the path that they undertook. We would like here to cite an expression of Dario Antiseri: ‘there is an urgent need, in the teaching of sciences, to make students *stumble* onto the problems’ (Antiseri 1977, pp. 111–112). If science is to be intended as *construction*, why are the students denied the access to the way in which this construction happened in the past and still happens now?

Some important experiences show that the active involvement of students in building, elaborating and communicating scientific paths transforms itself into motivation and learning. As an example of this, we can indicate an initiative called *Scienza under 18* (Science under 18), a regional council project, promoted by the Regional School Office of Lombardia (Italy), that has worked on the valorisation of the didactic experimentation and public communication of science by the students themselves for about a decade.[9]

In Italy, an important step, in accordance with the European and Italian debate, has been the creation in 2006 of the *Interministerial Work Group for the Development of the Scientific and Technologic Culture*, recently re-established as *Committee for the development of scientific and technological culture* (July 2010).[10] This institution has the role of drawing up guidelines to support the diffusion of scientific culture and the improvement of the quality and efficacy of education in the field. The documents produced make the same assumption that *science* is *culture*, a *way of knowledge*, and that as such it has to be explicated in the *curriculum*. The renewal of teaching proposed there does not only imply an in-depth study of the content matter of science but also of the discourse on science and scientific work, aiming at the student’s building and personal re-elaboration of the knowledge (Documento di lavoro 2007, pp. 3–4) in synergy with the professional development of teachers, for whom a lifelong training is necessary.

The case against superficial factual knowledge teaching leads to the identification of key objectives to be achieved: to update *teaching methods*, which, in fact, are not introducing young students to experimental inquiry; to lead them to the pleasure

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[9] http://www.scienza-under-18.org. Accessed 23 January 2011.

[10] http://archivio.pubblica.istruzione.it/argomenti/gst/ and http://www.istruzione.it/web/ministero/scienza-e-tecnologia. Accessed 23 January 2011.

of discovery and to a *taste for problem-solving*; to enhance systematic laboratory practice, to facilitate the development of activities like observation, measuring, handling and building; to diversify and enrich *didactic tools*, being too often only represented by *low-quality textbooks* (Fierli 2004); and to introduce a *humanised approach* with special attention given to *historic contextualisation*, 'to be considered as the understanding of the way and the time in which the concepts have been dealt with and the way the discoveries have been made'.

The aim is to make a *historical approach* to scientific disciplines and their connection to the *humanities* highly recommended; to situate the birth of concepts, of theories and of inventions in their social and cultural context; and to highlight the role of science and technology in the history of mankind.

In short, the finger is pointed against an idea of science presented without an epistemological, historical, dynamical and sociocultural approach, in which the description of the results has the priority over science making, in which scientific theories are presented as an absolute thing, to be learned in rote fashion, in the form of statements and principles, without any interdisciplinary approach. In addition, the new approach stresses the importance of the formative power of scientific culture, something that has long been neglected by the philosophic tradition and in Italian teaching practice (Morgese 2008).

However, though considered a priority in the Italian ministerial courses of study, these remain only hints and programme statements, since no specific document on the historical contextualisation of the *humanistic approach* and on the *connection between the sciences and humanities* has been issued (Morgese 2010b).

We recall the workshop, organised by the *Work Group* called *Per un nuovo liceo 'scientifico' nel XXI secolo. Fondazione culturale e rilevanza sociale* (1–2 April 2009) (Towards a new 'scientific' senior high school for the XXI century. Cultural foundation and social relevance), which constituted one of the preparatory tasks to the secondary school reform currently in force in Italy. The workshop moved in this direction, with the aim of promoting a debate among those in schools, universities and research on the cultural structure and the curriculum of senior high schools that award the science diploma,[11] which are the secondary schools with the greatest number of accepted applicants in Italy. The main issue was the reflection on the cultural and formative value of the science curriculum that it must be based on the '*holism of the project*, on the correct integration between the humanist-social component and the scientific one … not as a cold addition of the two disciplines but as a unified course' (Berlinguer 2009) in order to allow, for the different disciplines, the promotion of an integrated knowledge and the acquisition of scientific culture as the heritage of a community, not just for those who will take up a career in that field (Gouthier 2009a, p. 3, b).

Finally, though only as an initial recognition, in Italy, the importance of the issue was acknowledged through the introduction of references to this matter in the recent

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[11] Diploma is the qualification you get at the end of five years in high school; there are two types of Lyceum in Italy: *Liceo Classico* (Diploma in Classical Studies) and *Liceo Scientifico* (Diploma in Sciences).

National Guidelines concerning the specific learning objectives of high school courses. Specifically, it is prescribed for mathematics, physics and the natural sciences that the theories studied should to be set in the historical, philosophical, scientific, social, economic and technological environment within which they developed (see below).

Starting in the 2010–2011 school year, a *reform of the secondary level of education* was implemented in Italy.[12]

The objective of the new system is to revitalise the quality of secondary school education, intended as the ability to provide the student with 'the cultural and methodological tools for an in-depth understanding of reality, so that he can, in a rational, creative, active and critical way, deal with situations, phenomena and problems and acquire knowledge, abilities and skills in line with his capacities and personal choices and suitable for the continuation of higher level studies, for integration into social life and the world of work' (Regulation, Art. 2, Comma 2, cited in MIUR 2010a).

The reform was accompanied by the publication of ministerial reference documents. Two that are essential for a clear understanding of the new system are *profilo educativo, culturale e professionale (PECUP) dello student/educational, cultural and professional student profile (PECUP)* (MIUR 2010c) and *indicazioni nazionali/national indications* for high school courses of study (MIUR 2010b). The PECUP defines the student profile at the conclusion of the high school programme in terms of knowledge, abilities and skills. The document calls for a complete evaluation of all aspects of the student's scholastic work, in particular including 'the study of disciplines from a systematic, historical and critical perspective'. The centrality of the historical and critical perspective can be clearly inferred from the ministerial auspices. Firstly, these aspects are referred to as the result of common learning to be cultivated across the board in all six types of high school in the educational system. In particular, it is explicitly called for in the humanistic historical area,[13] in which the profile calls for the ability 'to contextualize scientific thought, the history of its discoveries and the development of technological inventions in the greater sphere of the history of ideas'. However, it is revealing that this proficiency is absent from the scientific, mathematical and technological area.

Thus, it can be inferred that the promotion of the development of this proficiency is basically entrusted to teachers of history and philosophy and not to teachers of scientific and mathematical disciplines. Secondly, the historical perspective is constantly referred to as the result of learning, even in the distinct high school courses of study. At the end of each high school programme, the student must be able appropriately and knowledgeably to place specific cultural products within their historical and cultural contexts.

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[12] This reform reordered the secondary school system into six types of academically oriented high schools and divided the professional institutes into two sectors, for a total of six courses of study, and the technical institutes into two sectors, for a total of 11 courses of study.

[13] One of the five areas that the results of cross-disciplinary learning are divided into at the academically oriented high schools. The others are the methodological area; the logical-argumentative area; the linguistic and communicative area; and the scientific, mathematical and technological area.

The national indications are the PECUP's guidelines for each discipline: teachers look to this document when creating their course outline so that their students can reach the objectives for learning and the acquisition of skills provided for in high school education. Therefore, the national indications basically focus attention on the disciplines to be studied, analysing them from two points of view: (1) from the point of view of the *competencies*[14] expected at the end of the course of study and (2) from the point of view of the ongoing *specific learning objectives*, aimed at the achievement of competencies, structured in disciplinary units relative to each 2-year period and to the fifth year. At the same time, a few core disciplines are identified: Italian language and literature, foreign language and literature, mathematics, history and sciences.

The guiding principles of the national indications are the following:

1. The *unity of knowledge*, with no separation of the 'notion' from its transformation into a skill. It is explicitly stated that 'Knowing is not a mechanical process, it implies the discovery of something that enters through the sensory process of a person who 'sees,' 'realizes,' 'tests,' and 'verifies,' in order to understand'.
2. *Interdisciplinarity*: the need to build a dialogue between the various disciplines for a coherent and homogeneous profile of cultural processes. The indications take on the task of highlighting the fundamental points of convergence, the historical moments and the conceptual connections that require the joint intervention of more than one discipline to be understood to their true extent.

As in the case of the PECUP, the national indications also make abundant reference to the historical dimension of knowledge, understood as 'reference to a given context' and to the need to promote that dimension in all disciplines of study to ensure that students obtain critical and mindful knowledge.[15]

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[14] The recommendations of the European Parliament and Council, 23 April 2008, in the European Qualifications Framework for Lifelong Learning, define this competency as 'Proven capacity to use personal, social and/or methodological knowledge, abilities and capacities in situations of work or study and in personal and professional development'.

[15] For mathematics, the student must know how to set the various mathematical theories studied in the *historical context in which they were developed*, understand their conceptual significance and have acquired a *historical-critical vision of the relationships between the main themes of mathematical thought and the philosophical, scientific and technological context*. It is explicitly stated that 'This articulation of subjects and approaches will be the basis for *establishing connections and comparisons* in concepts and methods with other disciplines like physics, natural sciences, philosophy and history'. For physics, at the conclusion of the course of study, the student will have learned the basic concepts of physics, acquiring knowledge of the *cultural value of the discipline and of its historical and epistemological evolution*. For the natural sciences, the subject matter should be proposed following the historical and conceptual development of the single disciplines, both temporally and as per *their links with the entire cultural, social, economic and technological context of the periods in which they were developed*. These links must be made explicit, through underscoring the reciprocal influences in the various spheres of thought and culture. A student completing the humanities high school course of study must also know how to contextualise scientific thought within the humanistic dimension. A student completing the scientific high school course of study must be aware, especially in physics, of the connection between the development of the knowledge of physics and the historical and philosophical context in which it developed.

The introduction in Italy of the reform was accompanied by a national convention[16] and by a series of seminars[17] aimed at teachers and principals, which included presentations by members of the commission for national indications and by representatives of the academic, productive and research fields. The relationships regarding the role and nature of science education in the reform show that the writers of the national indications were aware of the cultural value of the teaching of scientific disciplines with a historical, contextual and epistemological approach, referred to particularly in the presentations by Tommaso Ruggieri (2010), Giorgio Bolondi (2010), Nicola Vittorio (2010a, b) and Andrea Battistini (2010),[18] all of which are available on the website dedicated to the reform. What is missing, however, is any explicit reference to the results of national and international research on the use of the history and philosophy of science in teaching. Also missing are materials in this field of research which could be accessible for teachers on the web portal dedicated to the reform. Therefore, it seems that there is a gap between the national indications and the results of research.

Nonetheless, we would like to focus the reader's attention on one point: within the total hours for scientific disciplines, which are already few, there is no specific course time scheduled for the introduction of contents regarding the history and philosophy of science.

Moreover, the ability of the teacher to design interdisciplinary courses of study and to create connections between mathematics, the scientific disciplines and history and philosophy is entrusted to the free choice, competence and sensibility of the teachers themselves. Therefore, it is not part of their training, nor is it indicated as a practice that must necessarily be part of the teaching profession. The history of science is practically absent from the training of teachers, both pre-service and in-service.

Ministerial Decree 249/2010 (MIUR 2010d) redefined the initial training of Italian teachers at all levels. Therefore, starting in the 2011–2012 academic year, Italian universities instituted degree courses and Active Internship Training (TFA) courses for graduate students preparing to teach in the schools. The scientific field 'history of science and technology' is almost completely missing and is actually completely left out of the course of study for future teachers of history and philosophy at academically oriented high schools. The history of science and technology is taught to teachers who will teach philosophy, psychology and educational sciences in human sciences high schools, while it is an elective course (and with fewer course

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[16] National Convention *I nuovi Licei: l'avventura della Conoscenza*, Rome, 11 October 2010. Organising agency: Fondazione per la scuola della Compagnia di san Paolo, http://www.fondazionescuola.it/magnoliaPublic/iniziative/nuovi-licei/presentazione.html.

[17] Available at the previous link.

[18] Giorgio Bolondi, professor of geometry, faculty of economics and business, Università degli Studi di Bologna, and Nicola Vittorio, professor of astronomy and astrophysics, department of physics, Università degli Studi di Tor Vergata, Rome. They are both members of the commission for the national indications http://www.indire.it/lucabas/lkmw_file/licei2010/Decreto%20n.%2026%20del%20%2011%20marzo%202010.pdf.

hours than the mandatory courses) for future teachers of mathematics, sciences and technology in junior high schools (Bernardi 2011).

This appears to be a step back from what was required for the initial training of teachers prior to Ministerial Decree 249/2010. Previously, starting in 1998, teacher training was entrusted to specialised teacher training schools for secondary education (SSIS), a 2-year postgraduate training course required of anyone wishing to become qualified as a high school teacher. In the SSIS programme, study of the history of science and technology was obligatory for teachers of mathematics and scientific disciplines.[19] This experience was interrupted after nine cycles: in 2009, the activity of the SSIS was brought to a stop (Anceschi and Scaglioni 2010).

We wonder, then, how it is actually possible for teachers to teach science with an historical approach when this dimension is absent from their training. Moreover, a lot of questions arise: the guidelines are not based on the results of national or international research on the use of history and philosophy of science in science teaching, and there is a lack of availability of reference materials available for teachers. Finally, the time devoted to science teaching is far from enough to make possible an approach where history and philosophy of science can play an important role.

64.2 The Historical-Critical Approach: Concrete Experiences in Europe and Italy

In this section, we illustrate a few initiatives, projects and teaching activities fielded in Europe and Italy with the aim of carrying out the European recommendations outlined in the previous section of this chapter, and we illustrate the profile of some associations and research institutions dealing with education projects that have HPS/NOS as content.

64.2.1 Europe

In Europe, it is possible to identify a few recent experimental proposals that blend scientific education with the historical-critical approach.

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[19] The SSIS Apulia was a special case in that history of science and technology was a cross-discipline course for the teachers of all subjects (Dibattista and Morgese 2011). The aim of the course of 'history of science and technology' in SSIS Apulia was the didactic application of the discipline through the training of both science and humanities teachers. The result of the ten-year experience was the publication of a book, with the collaboration of some trainees of the various SSIS courses, that displays a series of actual proposals, usable case studies for the teaching of science in an interdisciplinary way and is based on the historical-critical approach (Dibattista 2008).

HIPST (*History and Philosophy in Science Teaching*)[20] has organised the collaboration of international research groups in order to produce and develop case studies for teaching and learning science with the historical-critical method oriented towards the discovery of NOS and the inclusion of the production of scientific knowledge in authentic contexts.

The theoretical assumption of the point of departure is that scientific concepts are more easily understood if presented in the historical context of their discovery, rather than presented in the decontextualised and systematic manner typical of the traditional didactic approach. The tools used were the production of teaching materials, in the form of case studies; documentation by the teachers involved in the study; and the formation of a solid network of science teachers, researchers and institutions which disseminate scientific culture, with the objective of collaboration in synergy for the implementation of the project and its follow-up (Höttecke and Riess 2009; Höttecke and Henke 2010, 2011).

In the initial phase of the project (1–16 months), a collection was made of materials related to the current teaching practices and activities in each partner country in the area of science teaching and learning, so as to establish a starting point on which to build the following project phases. The second phase of the project (16–28 months) was dedicated to the creation of a corpus of case studies on the basis of the national needs which had emerged in the previous phase, for example, on the basis of their adaptation to the study programmes in force in each nation. The corpus, translated into the various languages of the partner countries, was distributed and put into practice. The last phase of the project (29–30 months) was the period of the transfer of know-how, the fine tuning and distribution of the materials produced and their evaluation. All of the material produced was made accessible online.[21]

The Catalan Society for the History of Science and Technology (*Societat Catalana d'Història de la Ciència i de la Tècnica* – SCHCT) created a pilot course in the history of science for in-service teachers sponsored by the Department of Education (Departament d'Educació)[22] in Catalonia. The courses,[23] taught online with the Moodle learning management system, were held during 2009–2010 (Science and Technology through History) and 2010–2011 (the History of Mathematics and Science for Secondary Education) academic years, and more

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[20] The project, financed as part of the Settimo programma quadro (FP7, *The Seventh Framework Programme*, 2007–2013), had a duration of 30 months and concluded in July 2010, http://hipst.eled.auth.gr/. Project participants included ten partners from seven European nations and Israel.

[21] Available on the platform hipstwiki: http://hipstwiki.wetpaint.com/. The section of the corpus of *case studies* developed over the course of the project is at page http://hipstwiki.wetpaint.com/page/hipst+developed+cases.

[22] http://www20.gencat.cat/portal/site/ensenyament

[23] The course was presented at the symposium *La Història de la Ciència i de la Tècnica en l'Ensenyament i en la Formació del Professorat* dell'VIII *Congreso Internacional sobre Investigación en la Didáctica de las Ciencias* – Enseñanza de las Ciencias en un mundo en transformación, Barcelona, 7–10 September 2009, http://ice.uab.cat/congresos2009/eprints/cd_congres/propostes_htm/htm/inici.htm.

than 50 % of those enrolled completed the courses. The same introductory module was used to present the history of science and its use in teaching for the three modules specific to the teaching of mathematics, physics and biology. The greatest achievement of the initiative was that the teachers learned about the effectiveness of making use of primary sources, such as the writings of Galileo, Newton and Darwin. The greatest difficulty lay in the fact that the course was perceived as a university course in the teaching of the history of science, rather than as a tool developed specifically for school teaching (Grapì 2009, 2011; Massa and Romero 2009). The initiative is part of a change which took place in Catalonia between 2007 and 2008 with the adoption of a new curriculum for secondary education[24] which places at the centre of the teaching-learning of science the discovery of NOS, the historical context of scientific knowledge and the relationships between science, technology and society, and that, as a consequence, makes specific teacher training necessary. A similar situation can be found in the new study programme for mathematics, in which the knowledge of a few notions of the historical genesis of key events in mathematics is included (Grapì 2009).

Nevertheless, the history of science is not currently a mandatory discipline in the training of future teachers, and curricula in the history of physics, chemistry, biology or mathematics are optional. The CAP (*Certificado de Aptitud Pedagogica* – the certification for the qualification to teach in secondary school), in force until 2009, included the possibility to attend one or two sessions dedicated to the history of a particular scientific discipline. The current *Master en Formacion de Profesorado* includes in the Especialidad de Matemáticas only an obligatory module on ‘History of Mathematics’ and one on ‘Mathematics, Society and Culture’.

The current Spanish curriculum, issued by the Education Law (2006), includes HPS/NOS contents in compulsory and high school education through two ways: on the one hand, through the definition of the key competence in science as a cross-curricular keystone for the curricula of all science subjects and, on the other hand, through the design of common specific content for science subjects. The specific common contents designed for the curricula of science subjects involve a miscellaneous set of issues that can be grouped into the following categories: searching for information and using information technologies (ICTs); compliance with safety and operating standards in the laboratory; autonomy and creativity; processes of scientific inquiry; and science, technology and society.

Though the former categories include some aspects related to HPS/NOS issues, the latter display the core of HPS/NOS contents for science subjects. These include the recognition of the role of scientific and technological knowledge on social development and people’s lives; the recognition of the importance of scientific knowledge to make decisions about objects and about yourself; the assessment of the contributions of the natural sciences to meet the needs of human beings and improve the conditions of their existence; the appreciation and enjoyment of natural and cultural diversity; and the contribution to their conservation, protection and improvement, the recognition of the relations among science (physics, chemistry,

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[24] Ley Orgànica 2/2006, http://noticias.juridicas.com/base_datos/Admin/lo2-2006.html.

biology and geology) to technology, society and the environment and the potential applications and implications of their study and learning. Further, the institutionalisation of a specific subject, called Science for the Contemporary World, provides the longest and most systematic list of HPS/NOS content. The subject is compulsory for both science and nonscience students in high school (eleventh grade). It focuses on scientific and technological literacy by addressing current issues that are important for the general citizen.

The situation in higher education degrees is quite complex at the moment; on the one hand, similarly to Italy, it greatly depends on the research interests at each university; on the other hand, it is now changing due to changes to curricula to adapt them to Bologna guidelines, so that until the process is complete, little can be said about it. Finally, the initial training of teachers is also influenced by the development of the Bologna process. In the case of primary teachers, as science is for them just one subject among many other subjects to learn, the HPS/NOS contents are scarce. In the case of secondary and high school teachers (a single group in Spain from the view of initial training), the master's degree must prepare teachers to teach the science curricula, and thus, as the HPS/NOS curricular issues detailed above are compulsory, it must follow that HPS/NOS issues should be part of the master's training.

The ATLAS (Active Teaching and Learning Approaches in Science) group of the School of Primary Education at the Aristotle University of Thessaloniki has created a web tool (atlaswiki) that allows its teacher-users to find (and propose) relevant materials for the creation of teaching units, starting with the history of science (Kouloumtzos and Seroglou 2007).

Moreover, the Institute of Neohellenic Research of the National Hellenic Research Foundation in collaboration with the Laboratory of Science Education, Epistemology and Educational Technology (ASEL) of the University of Athens, Greece, started the History, Philosophy and Didactics of Science Programme (HPDST) (http://www.hpdst.gr) that is active in publishing journals and monographs of historical and scientific interest and in the organisation of symposia and conferences and has launched the project Hephaestus (Hellenic Philosophy, History and Environmental Science Teaching Under Scrutiny), funded under the FP7, currently ongoing and aiming to improve the activity of the programme in the field of history of science, educational activities and dissemination of scientific information and results.

More actions funded by the European Community through FP7 and are relevant to this review are as follows:

SONSEU (Science on Stage Europe), a European initiative designed to encourage teachers from across Europe to share good practice in science teaching, which publishes *Science in School*, a European journal for science teachers which often proposes papers about history and philosophy of science

MATERIAL SCIENCE, a partnership of six European Universities from Cyprus, Finland, Greece, Italy and Spain for the design and implementation of research-based ICT-enhanced modules on material properties. The project has a strand of educational resources based on the HPS (insights from the history of science and technology).

In France, the group Patrimoine, Histoire des Sciences et des Techniques (PaHST) at the University of Brest, in addition to the study of the scientific and industrial patrimony, is also active in the use of the history of science and epistemology in the teaching of the sciences. The group took part in the project ‘Mind the Gap’ in the cluster of projects financed by FP7 which attempt to meet the needs highlighted by the aforementioned Rocard report. In 2010, it organised a European workshop, History of Science and Technology Resources and Methods for Inquiry-Based Science Teaching (IBST), and it manages a block of courses at the University of Brest dedicated to HST, IBST and cultural mediation in science (Laubé 2011).

Still in France, the HPM[25] – History and Pedagogy of Mathematics – an international study group on the relations between the history and pedagogy of mathematics affiliated to the *International Commission on Mathematical Instruction* (ICMI), should be noted. By combining the *history* of mathematics with the *teaching and learning* of mathematics, the group aims at stressing the conception of mathematics as a living science, a science with a long history, a vivid present and an as yet unforeseen future. Among the group’s activities of particular interest are the satellite meetings at the *International Congress on Mathematical Education* (ICME), organised by ICMI every 4 years with the aim of disseminating and exchanging considerations on and practices in the use of the history and epistemology of mathematics in teaching.

Among the HPM’s recent activities, of particular interest was the organisation in Nantes on 4–6 July 2011 of the international conference *European Perspectives in the Use of History in Mathematics Education*, dealing with the developments of research in the field of the use of history in mathematics education, with particular reference to Europe.

Another activity worthy of note is the organisation of the *European Summer University on the History and Epistemology in Mathematics Education* (ESU). These are conferences which are moments of reflection and international exchange on the use of history and epistemology in mathematics education and bring together a network of teachers, researchers in education and historians. The proceedings are a landmark in the evolution of this approach. A high point of the ESU conferences is the teachers’ participation in the activities in close collaboration with the results of research. The initiative of organising a Summer University (SU) on History and Epistemology in Mathematics Education belongs to the French Mathematics Education community in the early 1980s.

In France, the network of IREMs[26] – Instituts de Recherche sur l’Enseignement des Mathématiques – organises conferences and seminars that focus on reflection, research and training teachers in how to integrate the historical approach in teaching mathematics. The research group also produces teaching materials (reprints of original sources, reports on classroom activities, teaching plans) which are the result of

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[25] For the history of the founding group in 2000, see the document available at http://www.clab.edc.uoc.gr/HPM/HPMhistory.PDF. The group’s website is at http://www.clab.edc.uoc.gr/HPM/INDEX.HTM. The HPM Newsletter is at http://grouphpm.wordpress.com/.

[26] http://www.univ-irem.fr/spip.php.

the hands-on classroom experience of teachers who participate in the IREM network. Ongoing activities worthy of mention include the organisation of the international conference *La didactique des mathématiques: approches et enjeux. Hommages à Michèle Artigue,*[27] 31 May–2 June 2012, which included among its topics of discussion consideration of the practices and research in the history and epistemology of mathematics in the teaching of mathematics (Plenary Lecture *Epistemology, History and Didactics*; Atelier *Epistemology and Didactics*).

A group of five European universities (Kapodistrian University of Athens, University of Pavia, University of Oldenburg, University of Cyprus, University of Thessaloniki) has created, as part of the actions of the European Union's Comenius 2.1, the STeT, Science Teacher e-Training project. This project, financed in 2006 as the continuation of a similar programme – the MAP project of 2004 – has created a series of tools which use case studies from the history of science to provide in-service science teachers with innovative materials to help them reconceptualise their views in some important teaching and learning aspects of science education and gradually transform their teaching practice. Currently, the Kapodistrian University of Athens coordinates five other partners (University of Flensburg, University of Brest, Polish Association of Teachers, Diamantopoulos School and the University of Winnipeg) in a new Comenius multilateral project named *Storytelling@Teaching Model* (S@TM) that started in 2011 and will end in 2013. This aims to enhance the professional development of science teachers by the use of case stories from the history of science, building a digital resource kit based on the storytelling teaching method.

The Scientific and Technological Research Council of Turkey (TÜBİTAK) is the leading agency for managing, funding and conducting research in Turkey. Thanks to funding provided by TÜBİTAK's 1001 programme, which funds scientific and technological research projects, the University of Marmara carried out a project for the development of teaching materials specifically developed for the teaching of modules on the history of science in secondary schools and tested its effectiveness on a sample of teachers of scientific disciplines (Irez et al. 2011).

One of the most complex projects for the integration of the history and philosophy of science into the coursework of preuniversity level students is the Perspectives on Science course which has currently been assessed as an Extended Project Qualification, an accepted qualification for university entrance in the UK. Developed by the Centre for Innovation and Research in Science Education, Department of Education, University of York, the course has the main goal of providing students with, in addition to the typical subject matter of the history, philosophy and ethics of science, the development of critical thinking skills typical of the epistemological approach. The goal is not only to prepare them for study in science after they leave school but, more generally, to foster an inquisitive, rational approach to life in general. For this reason, the course does not require acquisition of specific subject matter, but after an introductory phase in which the students learn how to use source materials and develop skills in philosophical and ethical argumentation and logical

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[27] http://www.colloqueartigue2012.fr/

reasoning, they must analyse case studies in the history of science and produce an individual research project. This dissertation takes the place of a final examination and must be defended orally. The teaching of the course and the evaluation of the final dissertation is carried out by the teachers from the institutions which have adopted the qualification[28]; this introduces the question of the training of teachers for a type of didactics based on the contextual and cultural dimension of science. This issue was addressed through the creation of teaching materials[29] and an *in-service training* programme.[30] The objectives of the course are to foster the mental skills that make it possible for the students to address science's 'big questions', to develop research and argumentation skills and to be open to ethical debate (Taylor and Swinbank 2011).

Moreover, the University of York, in partnership with the Nuffield Foundation, developed the Twenty First Century Science qualification, a suite of General Certificate of Secondary Education (GCSE) courses that 'meet[s] the needs, through flexible options, of those who will go on to be professional scientists and of those who will not'. The materials are designed to achieve scientific literacy through an understanding of ideas about science and science explanation. Basically, this is the realisation of the wishes from the Nuffield report that we have previously mentioned.

Still in the UK, mention should be made of the HIMED (History of Mathematics in Education) conferences, run by the Education Section of the British Society of History of Mathematics (BSHM). These were established in 1990 and promote the use of history in mathematics education (Fauvel and van Maanen 2000).

Finally, in the catalogue of the initiatives of scientific instruction collected by the STENCIL project (Science Teaching European Network for Creativity and Innovation in Learning (http://www.stencil-science.eu/)), it is possible to find numerous localised activities in European schools which use the history of science as a tool for teaching scientific disciplines. For brevity's sake, we will only point out here *Maths in Wonderland* in Romania, *Maths to Play* and *History, Maths, History of Mathematics* in Italy and *Energy is our Future* in Belgium.

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[28] In 2008, approximately 30 secondary schools participated in the project; in 2011, more than 700 institutes in the UK are taking advantage of this opportunity.

[29] A *Student Book* (Perspectives on Science Project Team 2007a) and a *Teacher Book* (Perspectives on Science Project Team 2007b) have been produced. Both are organised by *case studies* related to scientific problems and questions which are explored in their historical, epistemological and ethical dimensions and offer ample study materials. For example, the *Student Book* is organised as follows: Part 1: *Researching the History of Science,* Part 2: *Discussing Ethical Issues in Science,* Part 3: *Thinking Philosophically about Science*, and Part 4: *Carrying out a Research Project*.

[30] These are courses carried out during the school year both residentially and not. They introduce the teachers, of both scientific and humanistic disciplines, to the historical, epistemological and contextual approach to science, to the strategies for developing an active and dialogue-based method of teaching, to the development of *case studies* and to the writing of and *coaching* for the final dissertation.

64.2.2 Italy

In highlighting the existing situations, we distinguish between university research groups and professional teachers' associations.

64.2.2.1 University Research Groups

The university research groups listed carry out theoretical research on the methodologies for science teaching-learning, also developing operative projects for teacher training and orientation, and for the production of didactic materials.

University of Pavia: Group of History and Didactics

Historically, the oldest and better established group in Italy devoted to this matter is the Group of History and Didactics of the University of Pavia, which has worked with the aim of introducing the history of science in school curricula, especially through conferences and publications (Bevilacqua et al. 2001; Bevilacqua and Fregonese 2000–2003).

The activity of the group is focused on the identification of tools and methodologies that can contribute to the improvement of the teaching-learning of physics and the issues related to the initial and in-service training of junior and senior high school teachers, with an eye to developing innovative approaches to the teaching of physics, including the historical developments in the field of physics and the use of new technologies.

The *Group of History and Didactics* of the University of Pavia participated in the PRIN F21[31] project, *Percorsi di Formazione in Fisica per il 21° secolo/Physics Training Courses for the twenty first Century*, carried out in 2006 by University of Naples 'Federico II' under the scientific direction of Prof. P. Guidoni and in collaboration with various university groups of Italian researchers.

Within the F21 PRIN, the Pavia group was involved in the production of *teaching-learning sequences* (TLSs) for teachers of scientific disciplines, set in the wider panorama of research on TLSs. The TLSs implement the historical approach in the teaching of friction, in the belief that the role of the history of science is particularly effective and justifiable in this specific subject because it helps teachers:

> to clearly position recent developments, which have opened new areas and issues of research. A short historical overview, in addition to looking back at the characters and episodes of the past, serves to draw attention to recent events and future prospects, working together to

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[31] PRIN is the acronym which indicates 'research programmes of considerable national interest'. An overview of PRIN F21 is available at http://www.ricercaitaliana.it/prin/dettaglio_prin-2004020419.htm. For the part of the programme regarding the Pavia group, under the scientific direction of Prof. Paolo Mascheretti, see http://fisicavolta.unipv.it/didattica/SeqAttr/xxx.html and http://www.ricercaitaliana.it/prin/unita_op-2004020419_006.htm.

> show how this is a subject of current interest and study. It also makes it possible to provide simplified but effective insight into the issues regarding the subject, while learning about its complexity, linked to the diversity of materials and situations, and the theoretical uncertainties, revealed in interpretative controversies which have not yet been entirely resolved.

Additionally, the Pavia group has produced *the Pavia Project Physics – Gateway for the Circulation of Scientific Historical Culture* (http://ppp.unipv.it). The research carried out by the group is divided into three areas:

- Science history and philosophy: to position research on scientific knowledge within its cultural, institutional and social contexts and the context of the philosophies of nature that scientists explore and to more correctly contextualise the products of science
- Science education: research and experimentation with constructivist methodologies of teaching-learning which stimulate students' ability to formulate and resolve problems and to be active creators of their own scientific culture
- Digital technologies: the construction of hypermedia with differentiated approaches for different levels which facilitate the proliferation and personalisation of learning paths in physics

The products created by the group include:

- The analysis of *case studies* of the history of physics from Galileo to the modern day, with particular interdisciplinary focus on the relationships between scientific concepts and philosophical, religious and epistemological concepts
- Restoration and appreciation of primary sources, including the work of identifying and cataloguing collections of scientific tools and library collections
- Development and testing of learning activities for various scholastic levels on the basic concepts of physics, also through the use of ICT tools and multimedia, along with the production and testing of teaching modules for training physics teachers
- The creation of websites and teaching hypertexts with simulations of scientific experiences and the use of two-dimensional and three-dimensional presentations and animations to illustrate the theoretical principles of physics or how tools used in this field work
- A series of books, including essays, studies, catalogues of collections and teaching guides, also available on CD-Rom, exhibits, teleconferences and television programmes

These projects and products were tested as part of the course in physics, chemistry and the natural sciences for high school teachers.

University of Rome 'La Sapienza': Dipartimento di Fisica

Other important contributions in this direction are the activities of the research group of Dipartimento di Fisica of University of Rome 'La Sapienza' about the history of thermodynamics (Tarsitani and Vicentini 1991). Of particular interest is the didactic and research activity of Carlo Tarsitani, professor of the foundations of physics, regarding the history and philosophy of physics (developments in the field of physics in the nineteenth and twentieth centuries, history of quantum physics, conceptual foundations and the philosophical implication of quantum mechanics) and didactics of physics (the study of the conditions that could make possible the effective teaching of the physics of the twentieth century, in the final years of secondary school) (Tarsitani 2009).

University of Bologna: Physics Department

The Bologna group is identified around the didactic and research activity of Silvio Bergia, Grimellini Tomasini and Olivia Levrini. Here, we intend to focus on their considerations regarding the history and philosophy of science as effective tools in the teaching of physics in the SSIS programme (the *teacher training specialising course for high school teachers*) of Bologna. The materials developed for the didactic activity of the SSIS of Bologna concern space-time physics (from classical mechanics to the basic ideas of general relativity) and represent the results of a process of educational reconstruction, in which subjects' aspects are integrated with historical-epistemological and cognitive considerations with the following criteria: privileging the quality of knowledge rather than the quantity of notions to be transmitted, addressing topics and questions of twentieth century physics on the basis of a 'modern teaching' of classical physics, and fostering an image of physics as a 'cultural product' characterised by a coexistence of different interpretations of the same formalism and the interconnections with other cultural fields (Grimellini Tomasini and Levrini 2003).

University of Udine

The second level interuniversity master's degree in 'Didactic Innovation in Physics and Orientation' (M-IDIFO3)[32] (De Ambrosis and Levrini 2010), with headquarters at the University of Udine, is part of the Scientific Degree Programme (PLS) and is one of the most important Italian programmes for the orientation of teachers in the didactics of physics. A part of the didactic programme is dedicated to historical content (20 h of the history of cosmology from antiquity to Einstein and 30 h of laboratory work on the historical evolution of the concept of time).

University of Bari

We want to highlight two further innovative experiences in Italy regarding the teaching of science with an historical approach. They are both projects funded by the Italian Ministry of Education, University and Research (MIUR) in the sphere of funding designated for the dissemination of scientific culture (Law 6/2000) and

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[32] Coordinated by M. Michelini, Udine, as part of the Scientific Degree Project.

were both designed and directed by the Centro Interdipartimentale Seminario di Storia della Scienza dell'Università degli Studi di Bari 'Aldo Moro'/Centre for the Interdepartmental Seminar on the History of Science at the 'Aldo Moro', University of Bari. The seminar has, for many years, worked at training teachers, both pre-service and in-service, in the use of the historical and philosophical approach to science education.

The first project, *La storia della scienza va a scuola/The History of Science Goes to School*, was conducted during the 2009–2010 academic year and was a practical experience in introducing the history and philosophy of science into junior and senior high school classrooms in Apulia (Italy). The many schools which participated made use of the historical-scientific teaching modules through the case study approach. In the first phase, the participating teachers were trained by university tutors in how this particular teaching approach works. In the second phase, the teachers taught the modules in their classes, and, finally, these modules were presented at a concluding conference. The effectiveness of the project was also evaluated through questionnaires created specifically for this purpose.

Over 20 in-service teachers of scientific and humanistic subjects and over 400 students participated in the project.

The positive results of the research were the following: efficacy in communicating the scientific subject matter, learner (and teacher) openness to issues regarding the nature of science, the fact that the students gained a more comprehensive view of science and great student enthusiasm for publicly demonstrating the work they had done. Same critical points were the extra time and work that the teachers were required to devote to this project, on the one hand, to prepare the modules and, on the other, because of the lack of ad hoc teaching aids (Dibattista 2010). The project's products are 15 interdisciplinary didactic proposals in the form of case studies described by the teachers in a collective volume (Dibattista 2010), each one including an illustrative analytical file: the disciplines involved in the study case, the type of students it was aimed at, the prerequisites, the cognitive and metacognitive objectives, the methods and tools used, the timeframe, the proposals for verification and a bibliography.

The second project, *Il Racconto della Scienza – Digital Storytelling in Classe/The Story of Science – Digital Storytelling in the Classroom*, was conducted during the 2011–2012 academic year and was the result of a competition held in the junior and senior high schools of the Apulia region. Participants were asked to create multimedia products using the technique of Digital Storytelling to narrate a historical-scientific episode or the story of a scientist. Objectives were to promote the introduction of innovative approaches to teaching scientific disciplines, based on the history and philosophy of science, and solicit the production of highly personalised digital learning environments, created by the users themselves, starting from the specific didactic needs of each group-class and centred on narrative practice. Given the innovative nature of the methodology required to create the products, the teachers in charge of the classes entered in the competition completed a training programme on the history of science and audiovisual technologies, carried out at the University of Bari. Nineteen senior high schools and 13 junior high schools from the Puglia region participated. Over 40 teachers of scientific and humanistic disciplines and over 800 students participated in the project.[33] Twenty-four *Digital Storytelling* courses with historical-scientific content were produced by the schools. The project evaluations, carried out through the administration of questionnaires to teachers and students ex ante and ex post, are currently being processed. The project's final publication will include the description of the creation process of the winning Digital Storytelling courses, starting from the historical-scientific case study chosen as the topic; how the Digital Storytelling course fits into the framework of studies on digital learning environments; and the evaluation of the project, starting from the results of the questionnaires.

A recent project, *Performascienza. Laboratori teatrali di storia della scienza a scuola (Performascienza. Theatre Workshops of History of Science at School)*, involved historians of science and pedagogists of the University of Bari 'Aldo Moro' in the promotion of theatre workshops on history of science case studies in the junior and senior high schools of Bari and in the provinces. The project was carried out by *Scienz@ppeal Association*[34] of Bari and took place in 5 months of the school year 2009–2010. The project applied the dramatisation of *case studies* involving a wide range of actions, such as monitoring the scientific imagination of the teachers and of the students, the teaching practices of the science teachers and the receptiveness of the schools and of the territory in the diffusion of scientific culture. Finally, it involved an evaluation of the efficacy of the case study methodology, through the means of narration and drama, in building an interdisciplinary and complex *scientific literacy*. The products of the project are three videos which illustrate the process of carrying out the project in the three participating schools and a final publication (Morgese and Vinci 2010) which contains the narration of the case studies realised through theatre in the schools, the evaluation of the experience by the tutor teachers in each school, the evaluation of the project on the basis of the results of the questionnaires and a discussion of how the project fits into the framework of studies on the historical approach in science teaching.

64.2.2.2 Professional Associations of Teachers

Teacher associations listed below primarily perform guidance and training of teachers.

ANISN

The *Associazione Nazionale degli Insegnanti di Scienze Naturali/National Association of Natural Sciences Teachers* (ANISN)[35] is addressing scientific education using the historical-critical method.

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[33] The winners received their awards on 16 December 2011 at the Bari Cittadella Mediterranea della Scienza at an event attended by over 350 students and their teachers. The list of the digital storytelling winners and the reason for which they were chosen are available at www.scienzappeal.com.

[34] www.scienzappeal.com

[35] http://www.anisn.it/

ANISN is an association of teachers, scientists and enthusiasts founded in 1979 with the aim of promoting and increasing the professionalism of natural science teachers. Today, it is an authoritative organ that interfaces with institutions to promote the quality of science teaching in Italy and the exploitation of the best teaching practices. Periodically, the association organises conferences aimed particularly at teachers and publishes information about its activities through reports, newsletters and its website, which contains a wealth of information organised in various sections. One of these sections is dedicated to the history of science[36] and its use in teaching, in the belief that many topics in the natural sciences can be effectively addressed in the classroom through the historical approach and that the history of science is of great educational value 'since it makes clear how provisional the scientific models that man has created over the years are and points out the intersections that have always existed between science and other fields of knowledge'. Additionally, it 'makes it possible to define course outlines, presenting material in a progression mirroring that which occurred in history'. It is possible to download hypertexts containing syllabuses in the natural sciences.

To make explicit ANISN's contribution to the debate on scientific training at school, we would like to cite here the report *La visione della scienza costruita nella scuola/The Vision of Science Created at School* (ANISN 2007).[37] The report is the result of a study which revealed an alarming situation in the scientific disciplines: the way students learn these disciplines at school distances them from science since it does not make its meaning and importance explicit, but, on the contrary, they are presented in an authoritarian, difficult, boring, selective form, too specifically aimed at the mechanical application of strategies for the resolution of problems. The only exception seems to be the natural sciences, which are more able than others to explain their cognitive role in young people's education.

SCI-DDC

The *Società Chimica Italiana – Divisione di didattica della chimica/Italian Chemical Society – Chemistry Teaching Division* (SCI-DDC)[38] is pursuing a project to include historical-teaching modules in the core university curriculum of the undergraduate programme in chemical sciences. The experimental phase of the programme was carried out in the 2007–2008 academic year at the University of Basilicata. During the following year, the pilot course ('chemistry and its evolution') was taught at the University of Camerino with the participation of university and high school teachers and students in the province of Macerata. The topics covered in the pilot programme were the development of electrochemistry, nuclear chemistry, organic chemistry, inorganic chemistry, toxicology and physical chemistry and

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[36] http://www.anisn.it/storia_scienza.php

[37] This is a study on the perception of mathematics, physics, chemistry and natural sciences carried out through the administration of a questionnaire to 1,488 senior high school students in Italy.

[38] http://www.didichim.org/node/61

discussions with the students about the effectiveness of the historical approach to teaching chemistry. The initiative is an integral part of the Project Piano Lauree Scientifiche/Scientific Degree Project[39] in chemistry.

This proposal stems from the belief that the illustration of the historical depth of chemistry can notably improve the effectiveness of its teaching by showing where its concepts and practices come from and what their value is in terms of the work, organisation, time and passion of scientists in this field and critically focusing students' attention on concepts considered to be fully understood but which, instead, are unresolved.

The modules, taught by experts in history and the teaching of chemistry and science, are preceded by an introductory session on the historiography of the scientific disciplines and elements of the epistemology of the sciences. The subject matter modules are conducted as lessons logically inserted into the programme of host courses. The list of introductory lessons and subject matter modules is rich and varied. The former range from the epistemology of experimental cognitive science procedures to the historiography of science and chemistry. The latter illustrate the basic conceptual core of the subject, while taking an in-depth look at its historical development as related to the history of scientists and the social context of the scientific research.

Universities interested in this programme can sign up for a cycle of historical-teaching modules to be used on their campus.[40]

AIF

The activities of the AIF (*Associazione per l'Insegnamento della Fisica/Association for the Teaching of Physics*)[41] are also worthy of note. The AIF is a teacher's association founded in 1962 in Turin with the goal of popularising and promoting research in physics and the teaching of physics at all levels of school, from elementary school through to university. The association publishes and distributes scientific and teaching publications, organises teacher-training courses and conferences recognised by the MIUR (the Ministry of University Instruction and Research) and organises annual student competitions in physics. It is one of the implementing bodies (together with ANISN, SCI-DDC, the Leonardo da Vinci National Museum of Sciences and Technology Foundation in Milan and the City of Science in Naples) of the ISS (Insegnare Scienze Sperimentali/Teach Experimental Sciences) programme designed to monitor and carry out training initiatives for teachers in service under the form of research action for the improvement of the teaching-learning of the experimental sciences, with particular attention to teaching methodology.[42]

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[39] http://www.progettolaureescientifiche.eu/il-piano-lauree-scientifiche

[40] The complete list of modules can be found at http://www.didichim.org/download/Moduli%20storico%20didattici%20AA%202009-2010.pdf.

[41] http://www.aif.it/

[42] http://archivio.pubblica.istruzione.it/argomenti/gst/iss.shtml

The association is organised in work groups: the history of physics work group,[43] founded in 1985, studies issues regarding the history of physics in terms of their teaching value. Part of the group's work includes the organisation of a winter teacher-training school with the collaboration of experts in the field, a seminar on the history of physics at the national AIF conference, refresher courses for teachers in the history and teaching of physics. The goal of the initiatives for teachers regarding history is, first of all, to help them to reflect critically on the historical developments in the field of physics, to point out the interactions between the various scientific disciplines and to promote the value of teaching the history of physics within a general physics course through the possibility of increasing historical knowledge about the development of physics theories. Furthermore, they aim to recognise and enhance the cultural and social value of science in its historical dimension, analyse the characteristics of historical research, reflect on the sources and social and cultural context of reference, improve knowledge of primary and secondary sources and analyse the available teaching materials.

64.3 Conclusion

Despite the excellent quality of the projects, research and the practical experiences carried out in Europe and Italy, a series of criticisms must be reported:

(a) The European and Italian documents that we have mentioned do not always clearly insist on the use of the history of science. Rather, they call expressly for a study of the IBSE or PBL scientific disciplines.
(b) Even where the document is explicit, this does not automatically translate into curricular content, given the 'indicative' nature of said documents.
(c) The same thing happens with academic research or field experiences: they are not included in the formal programming of teaching in the schools. This is due to the lack of a connection between universities, teacher associations and ministries for public instruction. In fact, most of the time research and field experiences do not involve those responsible for didactic policy and programming on the national level. Nor do the didactic materials produced in these studies have a level of formalisation high enough for their inclusion in formal curricular programming.
(d) While the introduction of HPS in teaching aims to combine knowledge and interdisciplinarity, in most cases teachers show a natural reticence to abandon their mono-disciplinary structure. Planning multi- or interdisciplinary teaching units requires the collaboration of other teachers who must dedicate a certain number of hours to this type of planning; these hours are currently not included in the school organisation. Additionally, the materials produced in the practical experience of carrying out interdisciplinary units, even if published, remain outside the circuit of manuals and textbooks. It is well known that 90 % of teachers' scholastic programming is based on the latter.

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[43] http://www.lfns.it/STORIA/

Overcoming the difficulties listed here would require:

(1) A closer relationship between academic research, field experiences and instructional policies, involving the appropriate authorities as early on as in the planning of the research programmes.
(2) A high level of formalisation and promulgation of the teaching materials and learning units produced during the research and experimentation which would allow for their adoption in obligatory formal instruction.
(3) In any case, many studies have shown that modifying the curriculum is not very effective unless the teachers are motivated: 'It may be much more important to give teachers new frameworks for understanding what to count as learning than it is to give them new activities or curricula' (Langer and Applebee 1987, p. 87).
(4) The creation of institutional spaces in faculty meetings, specifically aimed at the planning of interdisciplinary courses.

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His research interests include the history of neurophysiology, with special attention to the mind-body problem. From a methodological point of view, Dibattista proposes an original model of scientific investigation of the historiographical texts based on computational linguistics. He is involved in promoting the teaching of science based on the history of science and, therefore, in a humanistic vision of training. He is a member of the History of Science Society, of Società Italiana di Storia della Scienza and of Società Italiana di Storia della Medicina. He is scientific director of a number of experimental projects for the application of history and philosophy of science to science education and teacher training in Italy.

He is the author of several contributions to journals in the history of science and computational linguistics and the following monographs: *Storia della Scienza e didattica delle discipline scientifiche* (Armando, Roma 2004), *J.-M. Charcot e la lingua della neurologia* (Cacucci, Bari 2003) and *Il Movimento Immobile. La fisiologia di E.J. Marey e C.E. François-Franck* (Olschki, Firenze, 2010). He is editor of *Gli Spaghetti di Mendel. Lezioni di Storia della Scienza per i Licei* (Cacucci, Bari 2008) and of *Storia della Scienza e Linguistica Computazionale. Sconfinamenti possibili* (FrancoAngeli, Milano 2009).

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Her main publication on teaching of science and science education is Morgese F. and Vinci V. (Eds), *Performascienza. Laboratori teatrali di storia della scienza a scuola* (FrancoAngeli, Milano 2010), and several other contributions in the field have appeared in edited books and journals.

Chapter 65
History in Bosnia and Herzegovina Physics Textbooks for Primary School: Historical Accuracy and Cognitive Adequacy

Josip Slisko and Zalkida Hadzibegovic

65.1 Introduction

Although the destiny of contemporary societies highly depends on sciences, the students' interest in becoming professional scientists is in alarming decline (Osborne et al. 2003). In Germany, for instance, the number of high school students who are interested in studying physics is significantly lower than the number of students that would like to spend their lives doing math, geography, art, and even politics (Hannover and Kessels 2004).

It is circular reasoning to say that for those students who somehow fell in love with physics, the science is always their first priority, being both most interesting and everywhere present. However, if one is looking for more convincing personal and social reasons why students have negative attitudes towards physics and science, then the answers point at the quality of their prior education and their interest in the subject (Mamlok-Naaman 2011), the academic plans (Crawley and Black 1992), the authenticity of science experiences in science education (Eijck and Roth 2009), the preferences of each student by nature or by the influence of teachers and/or parents, and even how they view scientists (Lee 1998). Recently, there were a few very informative review articles of the research literature related to the factors that affect positively or negatively students' attitudes towards science (Osborne et al. 2003; Krapp and Prenzel 2011).

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From these studies and their theoretical frameworks, one can conclude that the proper way to make physics and science intellectually and emotionally more attractive to young people is to choose a proper mix of teaching goals and methodology, along with an adequate usage of textbooks and other supporting materials. In other words, the learning goals, the content of textbooks, and the way physics is taught should play an important role in changing the negative attitude of a large number of students toward physics and the learning of physics. Nevertheless, one must always keep in mind that the process of building students' motivations, from a psychological point of view, is a rather complex theoretical and experimental issue (Lavigne and Vallerand 2010).

For some decades, science and physics educators (Klopfer 1969; Russell 1981; Matthews 1994/2014; Irwin 2000) have given multiple arguments why positive change in attitude towards science might be achieved by increasing the presence of history of science in physics education, especially in the content of textbooks and learning tasks. It was known that historical information might help to predict students' conceptual difficulties, with similar meaning to both the students and the earlier scientists (Wandersee 1986), and to design adequate learning sequences (Monk and Osborne 1997). The strength of these arguments was increased by the results of classroom-based studies (Klopfer and Cooley 1963; Solomon et al. 1992; Solbes and Traver 2003).

For changing students' views of science and scientists, it is convenient to use original materials from the history of science contained in books, museum collections about famous physicists, and multimedia materials based on the history of science. Unfortunately, the traditional (and frequently, superficial) way of using the history of science in science teaching and learning has typically involved brief biographical sketches of scientists, fragmented notes on inventions, and photos or drawings of scientists and their works, all mainly serving a decorative role.

The contribution of the history of science to science teaching and learning began in the second half of the twentieth century, both by historical studies whose results might be useful in teaching (Conant 1957) and by physics textbooks which had a strong historical flavor (Holton 1952). The culmination of that initial interaction between history and physics teaching was the Harvard Project Physics (Rutherford et al. 1970; Holton 2003). In the course textbook, historical episodes and information were not presented continuously but at places where they might foster learning and positive attitude towards science. Regarding the use of science history in teaching and learning school science, one can find now a great variety of considerations, didactical proposals, and experimental results that are very promising (Kokkotas et al. 2010).

Teaching that makes use of historical knowledge for designing learning tasks and cares about their real implementations produces good results related, for example, to the nature of science (Abd-El-Khalick and Lederman 2000; Galili and Hazan 2001; Abd-El-Khalick 2002), attitudes towards science (Mamlok-Naaman et al. 2005), conceptual learning in optics (Galili and Hazan 2000), or notion of experimentation styles in electrostatics (Heering 2000). In general, any use of historically oriented material in science and physics courses should be carefully analyzed in a broader perspective, determined by cognitive, metacognitive, and emotional aims of physics education (Seroglou and Koumaras 2001). History of science is also useful in better articulation of teaching (Binnie 2001; Wang and Marsh 2002) and prospective teachers' education (Riess 2000).

A main issue for textbook authors and analysts is the quantity and form of historical aspects in physics that will be included in a textbook. Laurinda Leite (2002) proposed a useful model for potential authors or educators who want to use historical episodes in their classes. According to that model, textbook analysis should discover how the history of physics is incorporated into the textbook body, including (1) variety, way, organization, and usage of historical information as one group of analysis elements and (2) accuracy of historical information, context in which the historical information appear, textbook consistency, connection between learning activity, and history of physics and references as other groups of analysis elements. The chosen historical episodes could be set out in a context useful for all learners (compulsory part) and additionally in parts reserved for only those who want to know more or, in other words, for talented pupils.

The methodology of using episodes from the history of science in physics textbooks should be based on four basic requirements:

1. Historical accuracy (use of historical episodes according to original articles, letters, notes, and patents constructed by scientists, as authentic historical documents)
2. Cognitive adequacy (concordance of the episode content with the taught topic and desired cognitive skills of pupils)
3. Motivational potential (potential of the historical information to increase pupils' interest in physics)
4. Didactical tools for the learning of the chosen content that are included in science curriculum

65.2 Characteristics of Primary School Physics Textbooks in Bosnia and Herzegovina

65.2.1 General Information on Analyzed Textbooks and Their Use of History

Before recent curriculum and policy changes (introducing 9 years long primary schooling), primary school education in Bosnia and Herzegovina was carried out in eight grades (corresponding to pupils' ages between six or seven years and 14 or 15 years). Due to the specific administrative organization, there are 13 different curricula in Bosnia and Herzegovina brought by 13 regional ministries of education (two at entity level, one at district level, and 10 at canton/county level). However, one can suppose that there are no limitations and restrictions for the authors in relation to the different curricula when organizing textbooks.

Among many physics textbooks used in different regions of Bosnia and Herzegovina, we analyzed only those written by domestic authors or published by

Table 65.1 Basic data on analyzed textbooks

Author	Textbook title	Year of publication	Total number of pages	Acronym
Esad Kulenovic	Physics for 7th grade of primary school	2006	197	A7
Esad Kulenovic	Physics for 8th grade of primary school	2006	214	A8
Nada Gabela, Hasnija Muratovic	Physics VII for 7th grade of primary school	2004	132	B7
Nada Gabela, Hasnija Muratovic	Physics VIII for 8th grade of primary school	2004	116	B8
Aziza Skoko, Kasim Imamovic	Physics 7 Textbook for 7th grade of primary school	2005	202	C7
Aziza Skoko, Kasim Imamovic	Physics 8 Textbook for 8th grade of primary school	2004	180	C8
Hedija Boskailo-Sikalo	Physics 7 Textbook for 7th grade of primary school	2004	205	D7
Hedija Boskailo-Sikalo	Physics 8 Textbook for 8th grade of primary school	2005	151	D8

domestic publishers. We carried out an analysis of four textbooks for 7th grade and four textbooks for 8th grade pupils used in primary school curricula in one of the Bosnia and Herzegovina entities – the Federation of Bosnia and Herzegovina (leaving out the physics textbooks in Republika Srpska) in the school year 2010/2011. Basic information about the analyzed textbooks is given in Table 65.1.

Textbooks A7 and A8, authored by Kulenovic, are now in their sixth edition. Textbooks B7 and B8, written by Gabela and Muratovic, are now in their second edition. The remaining four textbooks C7, C8, D7, and D8 are in their first edition.

It is important to stress that the primary school physical science syllabus in BiH does not explicitly require the usage of historical content to support physics learning. The presence of such information depends exclusively on authors' and editors' decisions.

Therefore, it is not surprising that textbook authors used various forms and amounts of historical elements. A quantitative analysis of textbooks, following the checklist by Laurinda Leite (2002), revealed a total of 15 different ways of using historical episodes of physics. These ways are presented in Table 65.2.

The largest number of historical elements was found in the C8 and C7 textbooks (25 % and 21.5 %, respectively). Notes about scientists had mostly a decorative role. Heterogeneity of historical information was noticed in textbooks C and D, whose authors belong to a younger generation of authors.

Table 65.2 Total number of contents in the textbooks for the seventh and eighth grade that take into account the criteria established in the checklist

	Count by grade level		
Historical content/information	7th	8th	Sum
Independent sections on the history of physics in some chapters	6	5	11
Historical notes integrated in the text	50	52	102
Note on the name of the units under the name of the scientist	11	9	20
Short biographical sketches of scientists (up to three lines of text)	17	43	60
Longer biographical sketch of the scientist	28	50	78
Scientists' pictures or drawings	47	65	112
Prominent scientific contribution (discovery, theory, law…)	43	26	69
Original documents/texts	13	1	14
Photograph or drawing of the invention or the experiments	12	19	31
Photograph of laboratory	3	5	8
Painting of historical episodes	5	3	8
Comical drawings of historical episodes	5	0	5
Legends as supposedly historical episodes	6	1	7
Other representations of historical episodes (stamps, banknotes…)	0	5	5
Historical episodes for those who want to know more	0	1	1
Overall historical content used	246	285	531

The most frequent historical elements were in a pictorial form integrated into the body text. Only one author gave references for such depictions. Notes, photos, and drawings of the same scientists (Galileo, Newton, Tesla, and Einstein) were present in the total sample of the analyzed textbooks. Historical information was generally intended to be used by all the pupils, whereas only one author planned to use historical data in a particular section titled "If you want to know more" (textbook A8).

Talented pupils could benefit from historical information that could lead to the formation of an idea, designing and carrying out an experiment, and formulating and applying a law or a theory. There were no instructions on how to obtain additional information about famous scientists, most influential experiments, theories, or original text, although such an information is relatively easy to be found today due to the Internet.

The comparison of the textbooks in relation to their inner consistency of historical elements showed that textbooks A and B are homogeneous, whereas C and D are heterogeneous in their presentations. Only textbook D provides references related to the materials used during their preparation. This can be seen as a generation difference because younger authors use more historical elements and materials.

Although there are important differences in the amount and type of historical episodes, the use of history of physics is generally reduced to superficial biographical notes that do not introduce pupils to the process of knowledge production in physics. Representation of the historical contents used in the analyzed textbooks in terms of percentages is given graphically in Fig. 65.1.

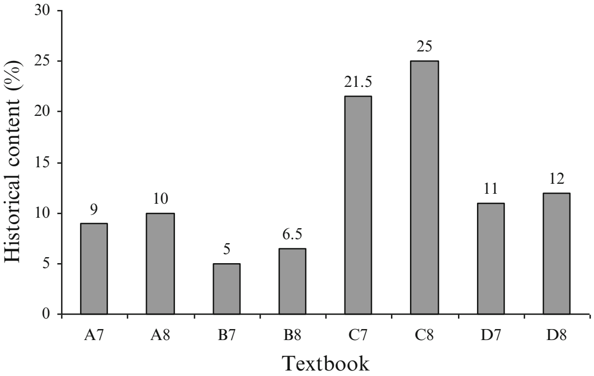


Fig. 65.1 Percentages of the overall content on history of science by analyzed textbooks

According to Fig. 65.1, it can seen that textbooks C7 and C8 contained remarkably higher amount of historical content compared to others, whereas textbook B7 had the smallest amount of historical content.

65.2.2 *Some Specific Examples of History Usage in the Analyzed Textbooks*

The elements of the history of science in the eight textbooks are used in a rather fragmented and superficial way. Mostly, they are biographical short texts describing the roles of physicists or of their inventions in very general terms. Frequently, texts are accompanied by physicists' pictures or other types of visual representation data, such as drawings, paintings, stamps, and banknotes.

The most important finding is that there are no explicit and meaningful learning tasks based on the history of science in these textbooks. The following presentation of the elements that appear most frequently will serve as an illustration of these not-for-learning-science uses of the history of physics in analyzed textbooks.

65.2.2.1 Biographical Portraits of Scientists

Sixty (11 %) short biographical sketches of scientists (up to three lines of text) have been counted. Basically, they provide the following information: birth and death year, nationality or country of origin, and the domain in which the scientist contributed by invention, law, or theory. Pictures or drawings that can be easily found on the Internet often accompany them.

Biographical information about scientists is usually included in a special position in the textbook page and always within a covered theme that is associated with the work of the scientists. There were three basic forms of presenting the life of physicists. The first is used in 32 % of the biographical notes, where scientists are presented in only one sentence associated with a picture or a drawing situated in a separate box containing a minimal amount of information: name and surname of the scientist, birth and death year, nationality or citizenship, and belonging to a scientific discipline (a physicist, astronomer, mathematician, chemist, or philosopher).

In the second form, textbook authors provide biographical notes about scientists ranging between two and five sentences (11 %), adding together data about their discoveries or inventions, or about their importance for civilization. In the third form, more informative data about scientists (57 %) are presented such as some short stories from their lives and works, ranging from 200 to 450 words. Such biographical stories about Newton, Galileo, Tesla, and Franklin can be found in the textbooks written by Skoko and Imamovic and by Boskailo-Sikalo.

65.2.2.2 Notes on Eponymous Names of Fundamental or Derivative Physical Units

In many instances, the history of science is used to inform about the origin of the names of units. From a total of 20 examples, the following two examples are presented (Boxes 65.1 and 65.2):

Box 65.1 The Origin of the Unit Name "watt" (D7, p. 150)

The unit of power is named the watt. Its symbol is W. This name was given in honor of the engineer Watt.

Box 65.2 The Origin of the Unit Name "coulomb" (B8, p. 9)

In the international system (SI) the unit of electric charge is the coulomb (symbol C). The unit is named after the French physicist Charles Coulomb who discovered the law of interaction of charges.

However, there was no information regarding neither the units that were used before the introduction of the International System of Units (SI) nor the reasons for introducing these new units. That curricular stand might be understood for those former units, like gauss, which are mainly out of use today. Nevertheless, some information about the usage of the mile, mile/hour, inch, or Fahrenheit degree as matter-of-fact units in some parts of the world (England, the USA) might be in place because students live and act in a globally connected world. This omission causes difficulties on students' understanding of Internet information and, further, could cause problems in their intercultural identification and recognition.

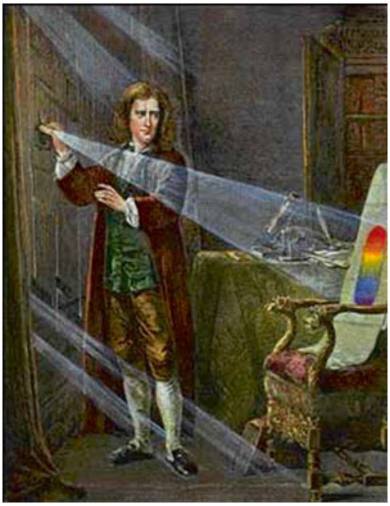


Fig. 65.2 Visual representation of Newton's famous prism experiment (D8, p. 149)

65.2.2.3 Short Historical Information About Experiments

Some important physics experiments, like Newton's prism experiment, are presented as a sentence-long information accompanying a picture (Fig. 65.2).

The text under this picture reads:

> Newton got a color spectrum by passing white light through a glass prism.

The picture used in the text is identical to the one available on-line at http://www.biographyonline.net/scientists/isaac-newton.html (accessed 10 November 2012).

This information is useless for the students' learning of the nature of light since Newton's main contribution was not the color spectrum but demonstrating via many cleverly designed experiments that the Aristotelian theory of light was wrong.

65.2.2.4 "Legendary History" of Physics

The "legendary history" of Physics is also presented in the analyzed textbooks. The following is one common example about Galileo and the Leaning Tower (Fig. 65.3):

> According to the legend, Galileo Galilei tried to calculate free fall time, observing a body falling from the Leaning Tower of Pisa. At that epoch, the time could not be calculated precisely as it happens nowadays with chronometers. Something like that was impossible. He discovered the law of uniformly accelerated motion by letting the ball rolling down an inclined plane as we indicated earlier. (C7, p. 102)

Fig. 65.3 The Leaning Tower of Pisa and Cathedral (C7, p.102) Available at URL: http://www.7wonders.org/europe/italy/pisa/leaning-tower/ (accessed 10 November 2012)

In this extract the authors incorrectly describe both the legend and the real experiment carried out by Galilei. The legend says that Galilei disapproved Aristotle's idea that "heavier bodies fall faster" by dropping two cannon balls of different weight, which hit the ground at the same time. So, "calculation of time" is not part of the legend.

Galilei's "inclined plane experiment" (Galilei 1954) was a highly discussed theme in the history of science. Repeating Mersenne's critique, Koyre (1968) claimed that Galilei neither carried out this experiment nor other experiments he described in his published books. Nevertheless, thanks to Drake's ground-breaking investigations of Galilei's handwritten notes (Drake 1973, 1975), it is now generally believed that Galilei did actually carry out his experiments.

Taking into account Galilei's description of the theory that became the basis for the "inclined plane experiment" (Galilei 1954), it is necessary to stress that Galilei didn't design that experiment to discover the law of uniformly accelerated motion, as it is claimed in the text above, but to check out if that motion is a motion with constant acceleration. For such a motion, Galilei knew the theoretical relation between distance covered and time elapsed: the covered distance is directly proportional to the square of time elapsed.

Galilei's worldview led him to believe in such a possibility for free fall, and he wanted to have experimental evidence. He repeated the experiment increasing progressively the inclinations. The data he got were the expected ones according to the theoretical model (distance covered directly proportional to the time squared). This made him to infer that very likely free fall (motion down the plane with 90° inclination) is also a uniformly accelerated motion.

Even more erroneous treatment of Galilei's "thought experiment" regarding the logical possibility of forceless motion has been found in the analyzed textbooks. This thought experiment was given in the form of Socratic conversation between Salviati and Simplicio in "Dialogue concerning the two chief world systems" (Galilei 1967). Salviati led Simplicio to accept that (a) a ball rolling down an inclined plan increases its speed; (b) the same ball rolling up an inclined plane decreases its speed. After that Salviati formulated a very disturbing question for Simplicio (a person advocating the Aristotelian view of motion):

> Now tell me what would happen to the same movable body placed upon a surface with no slope upward or downward. (Galilei 1967, p. 147)

Two different treatments of this "thought experiment" by Galilei are presented below. The first example is extracted from the A7 textbook and the second from the D7 one (Boxes 65.3 and 65.4). The illustration showed in Fig. 65.4 is one similar to the A7 and D7 illustrations:

Box 65.3 Textual Description of the Experiment (A7, pp. 93–94)

When a small ball is rolling down an inclined plane of a certain height, it will continue to move uniformly in a horizontal surface, and then climb up another inclined plane to the same height from which it started. In the absence of friction, this climbing will be independent of the distance traveled horizontally and the slope of the inclined plane along which the ball climbs. On this basis, Galileo concluded that the body moving at a certain speed on a horizontal surface in the absence of friction and other resistant forces will continue to move uniformly forever. This conclusion is known as Galilei's principle of inertia.

Box 65.4 Textual Description of the Experiment (D7, p. 121)

Galileo Galilei observed the movement of the ball rolling down a double inclined plane in which the slope of the right part can be changed. If we reduce the slope of the right inclined part, and the ball rolls down from the same position, then the ball rolls up the right inclined part to the same height but the distance it must go along the slope is greater. The maximum distance is achieved when the ball moves in a horizontal surface at the right side.

Every body persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it.

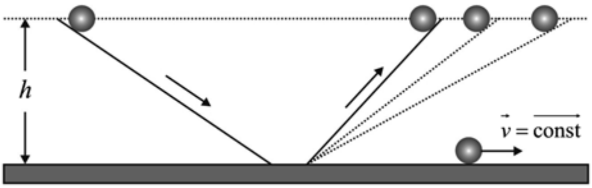


Fig. 65.4 An illustration of Galilei's "thought experiment" on inertial motion (A7, p. 94, and D7, p. 121)

> We describe Galilei's experiment and his conclusion…(A7, p. 93)

As it can be seen, both treatments erroneously suggest that this "thought experiment" was a real experiment, carried out by Galilei.

Erroneous and superficially simplified presentations of physics history in textbooks, especially of those important episodes that are connected to research-based historical facts, are not an exotic syndrome of the authors from Bosnia and Herzegovina. On the contrary, it is a rather global phenomenon, as recent Niaz's books (2008, 2009, 2010) show convincingly. This unsatisfactory situation is caused, on the one hand, by the weak quality control in physics teaching and textbook writing (Slisko and Hadzibegovic 2011), which makes possible the invention of (erroneous) historical information due to the ignorance of the authors, reviewers, and users. This invented information enters and stays in the textbooks. On the other hand, there is an inclination of the research community towards the "backwards written history," which is common in the way "normal science" is presented in physics textbooks (Brackenridge 1989).

Backwards written history refers to special classes of falsified history in which historical episodes are presented in a way that leaves the impression that modern concepts and procedures were used when, in fact, they didn't exist in that particular time. So, it is not a physics history as it really was, but a physics history as it might have been but was not. One paradigmatic example of *backwards written history* is the known (erroneous) claim in the physics textbooks that Cavendish measured the value of the gravitational constant, although his research question and reasons were different, and the very idea of the gravitational constant did not yet exist (Slisko and Hadzibegovic 2011). A misleading interpretation of the Greek atomism as an anticipation of the modern scientific atomic theory is also common in philosophical literature (Chalmers 2009).

Among 531 examples of use of historical information detected in the analyzed physics textbooks for primary school in Bosnia and Herzegovina (BiH), one example was chosen, found in the D8 textbook, to explore how primary school students (pupils) make sense of superficial and incomplete presentations of an historical episode. Up to date, this is the first study of this kind related to the uses of history in BiH physics textbooks.

Our objective is to show by some initial data that such presentations are not cognitively adequate for pupils. Namely, the pupils as sense-making persons try to provide the missing information to establish the story coherence. This process, as it will be shown later, is potentially damaging for the pupils' learning because the missing information they provide may take forms that neither correspond to the historical facts nor is physically possible.

65.3 Chosen Historical Episode for Research with Primary School Students: The Measurement of the Speed of Sound in Water

The chosen historical episode is the measurement of the speed of sound in water, carried out by Jean-Daniel Colladon in 1826 at Lake Geneva (Colladon 1893). That measurement was very important for checking whether the theoretical formula for the speed of sound in combination with the measured value of the water

Fig. 65.5 The boat with underwater bell and mechanism for sending light signal

compressibility would predict a correct value of the speed of sound in water. That research was planned and successfully accomplished by Colladon and Sturm. For that particular research they received the first award of the French Academy of Science. Although these contextual details would be very important in analyzing textbook presentations of the Lake Geneva Experiment at higher educational levels, we will not deal with them in the analyzed accounts for younger students (grade VIII in Bosnia and Herzegovina and grade IX in the UK).

65.3.1 Design and Results of the Original Experiment

The basic ideas of the experiment design at Lake Geneva were as follows: An assistant of Colladon (Sturm was then in Paris and did not take part in the experiment!), being in one boat, sent simultaneously an underwater sound signal and a light signal in air. The sound signal was produced by striking an underwater church bell with a hammer. A complicated mechanism simultaneously ignited the gunpowder and struck the bell on the first boat (Fig. 65.5).

Colladon himself was in the second boat with a long horn immersed in the water, attached to his left hand (Fig. 65.6). The immersed end of the horn had an elastic membrane that would vibrate when reached by the underwater signal, making possible for Colladon to hear the sound of the bell. He activated a chronometer (stopwatch) using his right hand when he saw the light signal coming from the first boat and stopped it when he heard the sound of the bell that came through the water.

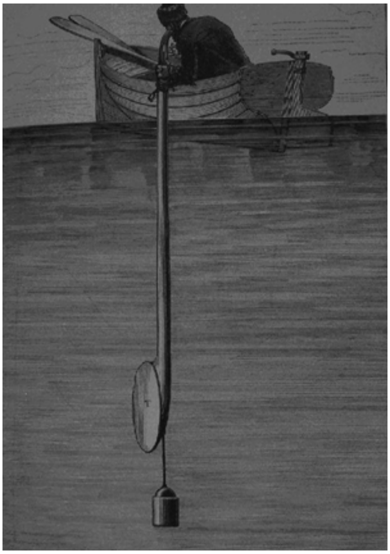


Fig. 65.6 The boat with underwater horn is used to hear the sound produced by bell

The distance between the two boats was carefully measured by triangulation methods and it was found to be 13,478 m. The mean time the sound needed to travel through water between the bell and the horn was 9.4 s. These values result in a value of 1,435 m/s for the speed of sound in water.

65.3.2 A Textbook Presentation of the Lake Geneva Experiment in Bosnia and Herzegovina

Only one textbook (D8) presented the experiment carried out by Colladon at Lake Geneva, combining verbal and visual information. The textual part is as follows:

> A physicist and his assistant were in two boats 1,500 m away from each other. A bell on a rope was immersed in the water from the first boat with the assistant in it. His task was to hit the immersed bell with a hammer and simultaneously send a light signal. The physicist with a long horn was in the second boat. One end of the horn was immersed in water, while the other end of the horn was held by the physicist near his ear. The moment he saw the light signal, the physicist switched the chronometer on and measured the difference of time between the moment he saw the light and the moment he heard the sound. The delay of the sound signal was one second. The physicist concluded that the sound needed 1 s to travel 1,500 m through water, and that the speed of sound in water was 1,500 m/s. (D8, p. 102)

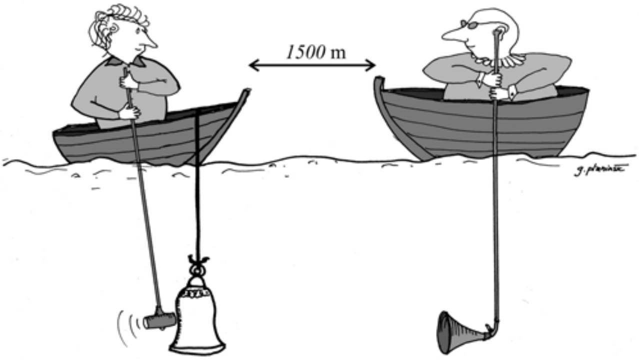


Fig. 65.7 The drawing of Colladon's experiment, similar to the picture in D8, p. 102

The visual representation of the experiment is a drawing of the situation (Fig. 65.7)

This example is analyzed from two perspectives. The first one is its historical accuracy or, in other words, whether the description of the particular episode is precise enough. It is easy to see that the author presents false experimental data, giving for distance and time the values of 1,500 m and 1 s, respectively.

The second, even more important one is the cognitive perspective: Is the presentation structured in a cognitively adequate way giving thus pupils an opportunity to learn how physics in its experimental domain works, without inducing students to accept some erroneous ideas?

Comparing verbal and visual descriptions, it is possible to detect incoherence between them, which would be a learning obstacle for all students who try to comprehend fully the way the experiment was carried out. Namely, the drawing gives students no idea of how the light signal was sent as, according to the drawing, assistant's both hands are employed to hit the underwater bell by the hammer. The other, potentially enigmatic part for students, is how the physicist can switch on and off the chronometer if, again, both of his hands are used to hold the horn under water.

So, the above textbook presentation of the historical experiment in which the speed of sound in water was measured is:

1. Historically inaccurate (the values of the distance and time are arbitrarily invented)
2. Depersonalized (Colladon became an anonymous physicist)
3. Cognitively inadequate (neither the text nor the drawing gives students an opportunity to comprehend fully how the experiment was carried out)

65.3.3 Another Textbook Presentation of the Lake Geneva Experiment

To put this particular textbook presentation in a broader international perspective, it is instructive to look at another presentation of the same experiment which comes from the UK:

> Newton's work predicted that sound should travel faster in water than in air.
>
> This was proved by an experiment on Lake Geneva in 1827. An underwater bell was rung at the same time as some gunpowder was lit. On another boat 14 km (9 miles) away, the flash was seen (at night) and the sound was heard through the water by a large ear trumpet dipping into the water (Johnson et al. 2001, p. 82, italics added).

The follow-up tasks for the students are:

1. Think about the Lake Geneva Experiment, and sketch what you think the apparatus looked like on each boat.
2. With a distance of 14 km the sound took 10 s. What was the speed of sound in water? (Johnson et al. 2001, p. 82, Question 3)

Regarding historical accuracy, the UK textbook authors present rounded values of the distance and time that are close enough to the original ones. The year of the experiment is not the correct one and corresponds to the year the results were initially published.

It is very good that the authors asked students to calculate the speed of sound in water instead of giving them its value (task b).

It is also a good idea to suggest students to sketch how the experiment was carried out (task a), although it might be a very demanding drawing task for students due to the fact that the verbal description is really incomplete and hardly can lead any student towards necessary technical details of the design (see Figs. 65.5 and 65.6). In addition, the impersonal form of the narrative about the experiment might be a serious obstacle for students' sense making and learning.

Being inspired by the drawing task (1) in the UK textbook presentation, in our research, described in the next section, we explored how students visualize and make sense of incomplete verbal and visual information of the chosen textbook presentation of the historical experiment for measuring the speed of sound in water.

To make our discussion of the process followed by the students as they try to understand a given text more understandable, it is necessary to remind readers of the ideas of Kintsch (1998) and Kintsch and van Dijk (1978) regarding text comprehension. They claim that two basic steps are important in order to understand a text: the construction of the text base and the construction of the corresponding situation model. The text base is drawn from the propositions of the text, and it expresses its semantic content, both globally and locally. The situation model is constructed by integrating the textual content in the reader's knowledge schemes. Any text for which the reader is unable to construct a correct situation model is not understandable. If the text is taken from a textbook, then such a text is not cognitively adequate for students learning.

The research procedures to find out details of the situation models students construct for a textbook presentation might be word based or drawing based. As already indicated, the second option was selected. This option is used in research on students' science learning (Benson et al. 1993; Edelson 2001; Köse 2008; Shepardson et al. 2011), students' comprehension of scientific texts (Schwamborn et al. 2010; Leopold and Leutner 2012), and students' images of scientists (Farland-Smith 2012) or mathematicians (Picker and Berry 2000).

Up to date, as far as we know, this is the first research using pupil's drawings as a tool to assess comprehension of textbook presentation.

65.4 Basic Research Description: Participating Pupils, Worksheet Design, and Evaluation

65.4.1 Participating Pupils

A group of 151 pupils participated in this research. The locations of the schools and pupils' gender characteristics are given in Table 65.3.

Locations of the PS1–PS3 were situated in Sarajevo Canton, whereas location PS4 was situated in Central Bosnia Canton. It is worthy to mention that these two Cantons were randomly selected and have different education policies.

Pupils were given text worksheets (Box 65.5) containing only written information on the Lake Geneva Experiment from the textbook D8 and four tasks. The original picture showed in the D8 textbook was not attached.

65.4.2 Worksheet Design and Evaluation

The first task was to make a drawing based on the information given in the text worksheet. The second task was to explain in textual form all the difficulties they encountered in the first task. After that, the students were given the original drawing from the D8 textbook, and they were told to complete the third and fourth task.

Table 65.3 Distribution of pupils by school, number of class unit, and gender

School	N (Classes)	Female	Male	N (Pupils)
PS1	1	11	11	22
PS2	1	13	6	19
PS3	3	22	28	50
PS4	3	30	30	60
Total	8	76	75	151

Notes: *N* number, *PS* primary school

Box 65.5 The Content of the Worksheet

(WS)Pupil’s Code:

Speed of Sound in Water

The following text describes the experiment used to measure the speed of sound in water in the nineteenth century:

A physicist and his assistant were in two boats 1,500 m away from each other. A bell on a rope was immersed in water from the first boat with the assistant in it. His task was to hit the immersed bell with a hammer and simultaneously to send a light signal. The physicist with a long horn was in the second boat. One end of the horn was immersed in water, while the other end of the horn was held by the physicist near his ear. In the moment he saw the light signal, the physicist switched the chronometer on and measured the time difference between the moment he saw the light and the moment he heard the sound. The delay of sound signal was one second. The physicist concluded that the sound needed one second to travel 1,500 m through water, and that the speed of the sound in water was 1,500 m/s.

Questions/Tasks

1. Insert into the box below your own drawing according to the given text.

2. If any part of the given text is not presented in your drawing, then describe that part by your own words. Explain why it is important to understand this experiment, and why it might be difficult to draw it.
   Answer:

3. Describe your feelings and thoughts about your own drawing and the drawing from the textbook that has been shown to you.
   Answer:

4. Express your opinion here about your today learning experience.
   Answer:

The third task asked the students to give feedback on their thoughts and emotions after the presentation of the original drawing. The feedback was given verbally in a classroom in the presence of one of the researchers (Z. H.). Finally, the students were asked to complete the fourth task by expressing their attitudes towards active and passive physics learning and to compare this classroom experiment with the standard education they received previously.

The first task was used to assess the ability of pupils to construct an adequate situation model according to Kintsch's terminology.

To track pupils' achievements, a scoring scheme was developed specifically to evaluate pupil's understanding of the given text. According to this, each of the following scoring rubric elements was graded with one point (seven points in total):

1. Any drawing according to in-class reading (given text)
2. Drawing similar to the D8 (the same number and choices of drawing elements)
3. Device for sending light signal from the first boat
4. Instrument/device for time measurement placed in the second boat
5. Sound wave representation in sinusoidal shape
6. Data of distance (1,500 m)
7. Velocity value (1,500 m/s).

65.5 Results and Analysis

The statistical data based on the results of the 151 pupils who responded to the questions and solved the tasks in the WS were analyzed. Achieved scores within different groups of pupils (male or female and pupils from different cantons) were tested for normality of distribution with Kolmogorov-Smirnov and Shapiro-Wilk tests. Since the distribution was not normal, the scores were expressed as median and compared within different groups with Mann-Whitney test. Pupils reached the median value of four points.

There were no significant differences in scores between pupils from different counties (Mann-Whitney U: 2602.5, $p = 0.62$) or between male and female pupils (Mann-Whitney U: 2,740, $p = 0.68$). However, the minimum score achieved by the male pupils was 2, whereas the female pupils had a minimum score of 0 (Table 65.4).

A maximum score of seven was accomplished by five (3.3 %) pupils. Pupils were classified into five groups according to the number of achieved points as follows:

Group I: 0–3 points
Group II: 4 points
Group III: 5 points
Group IV: 6 points
Group V: 7 points.

The distribution of the pupils among the above mentioned groups is shown in Fig. 65.8.

Pupils' results that scored according to the seven expected drawing elements (items) are presented in Table 65.5.

The most important result of this research was the opportunity for each pupil to actively participate in drawing and after-drawing discussions. According to their

Table 65.4 Basic statistical data

	Male, N = 75	Female, N = 76	Total, N = 151
Median	4	4	4
Range	5	7	7
Minimum	2	0	0
Maximum	7	7	7
Achieved/total points (%)	61	62	61

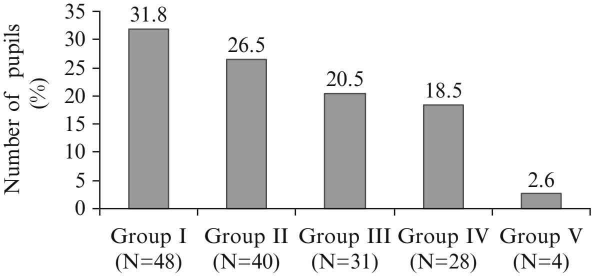


Fig. 65.8 Distribution of pupils' groups by achieved points

Table 65.5 Percentage of pupils that scored in each item

Expected drawing item	Grading point	Frequency (%)
Any drawing according to the text	1	99.3
Drawing identical to the D8	1	28.5
Device for sending light signal from the first boat	1	11.3
Instrument/device for time measurement placed in the second boat	1	15.2
Sound wave representation in sinusoidal shape	1	58.9
Data of distance (1,500 m)	1	79.5
Velocity value (1,500 m/s)	1	18.5

teachers' testimonies, many of them find common activities in physics classrooms to be boring and uninteresting because of their passive roles.

Surprisingly, the number of pupils who used sound wave representation in sinusoidal shape was high (58.9 %). This is interesting because in the primary school curriculum, they do not meet graphical representation of the sine function or analytical representation of wave phenomenon. Obviously, this is an influence from their out-of-school experiences.

Among the 151 pupils, 79.5 % considered the sound velocity value as an important detail that they needed to include in their drawings. However, it was discovered in a posterior class discussion that around 60 % of them believed that the sound velocity in air is greater than in water.

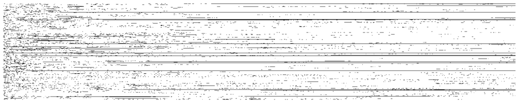


Fig. 65.9 A pupil's drawing with both light-sending and time-measuring devices

Data analysis is separated into four parts.

Part A
Basically correct drawings were given by 39 % of pupils, with *both light signal sending and time-measuring devices* being inserted into drawings that were similar to the one from the D8 (Fig. 65.9). Although their devices do not correspond to the actual devices used in the experiment, it is interesting that four out of 10 students were able to construct an adequate situation model from the given text. So, despite that some of the primary school students (from 14 to 15 years old) feel bored by the common physics learning activities, they grasped the experimental situation in a more accurate way than the artist who created the textbook drawing and the editor and reviewers who approved it!

Part B
Some pupils (11 %) revealed an abovementioned "backwards written history" approach to the reconstruction of the historical episode by drawing contemporary devices, such as lasers or digital watches. They can be hardly blamed for this "error" because that was their solution to the problem of cognitively inadequate narrative, which is unclear about the light-sending procedure or mentions time-measuring instruments that might be unknown to pupils (chronometer).

Part C
Only eight pupils (5 %) answered the second WS question. Such a poor participation can be understood within the context of classroom culture: these pupils are rarely asked to express and describe in their own words their thinking as well as the learning obstacles they encounter. This explains why it was preferred to use the drawing mode instead of the verbal mode to explore the students' comprehension of the text.

Nevertheless, what these eight pupils wrote is very informative. Five of them indicated that they did not know how to present sound after the light signal was sent. Two students wrote down that they found difficult to draw a "broken" thing (hammer, bell, horn). It is a nice example of how complex a drawing task might be for students who would like to apply their prior knowledge from optics. One student wrote that he did not know how to represent the situation of the physicist in the second boat seeing the light signal.

Part D
The students finally had the chance to observe the textbook's drawing and make comparison between the textbook's and their own drawing. This resulted to a series of different comments. According to the comments and expressed emotions, the pupils can be divided into three groups: satisfied, frustrated, and indifferent.

The first group (G1) consists of 78 satisfied students (52 %) who expressed positive emotions and gave affirmative comments after comparing their drawings with the textbook drawing shown to them by the researcher (Z. H.). The most prevalent keywords they used were "happy, satisfied, and pleased."

The second group (G2) consists of 10 frustrated pupils (7 %) who had negative comments and emotions about their drawings after the comparison with the textbook drawing. They used keywords like "disappointed, sad, frustrated, and embarrassed."

The third group (G3) consists of 63 indifferent pupils (41 %) who had no written comments or opinion presented in the WS.

In G1 four different subgroups of pupils can be distinguished who used different descriptions of their drawings as follows:

G1-a: "My drawing is *similar* to the drawing from the textbook" was stated by 61 pupils (72 %).
G1-b: "My drawing is *the same* as the drawing in the textbook" was stated by 7 pupils (8 %).
G1-c: "My drawing is *different* from the drawing in the textbook" was stated by 11 pupils (13 %).
G1-d: "My drawing is *better (richer)* than the drawing from the textbook" was stated by 4 pupils (5 %).

It is interesting to note that in the G1-a subgroup, there are pupils whose drawings include the same elements as the drawing from the textbook (case of 28 of pupils). Twenty pupils drew both signal devices, while the drawing from the textbook does not show any signal. Seven pupils used a light source (lamp, laser, sun-mirror) in their drawing, and six pupils had the time-measuring device in the boat with the physicist.

In the G1-b subgroup some pupils' drawings actually were different. Two pupils used two assistants in the boat; others drew a signaling device in the physicist's boat.

In the G3-c subgroup the pupils explicitly stated why their drawings were better or richer than the drawing from the textbook:

> My drawing is better because I have a lamp and a timepiece which is not included in the original drawing.
>
> My drawing is a better one. In the drawing from the textbook the light is not shown, the sound visualization is not found and the distance between the two boats is poorly represented.

Pupils from G2 believed that their drawings differed from the textbooks' drawing because they did not draw the physicist and his assistant (boats without people, for example). This is a very important detail, because both persons were mentioned

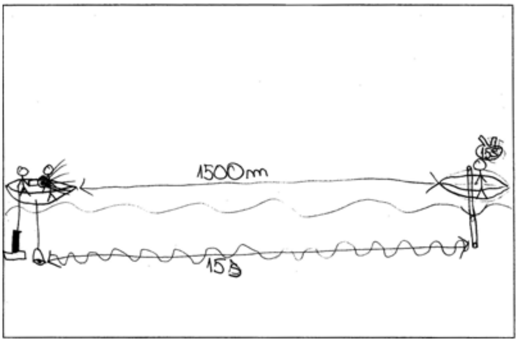


Fig. 65.10 Two experimenters in the first boat

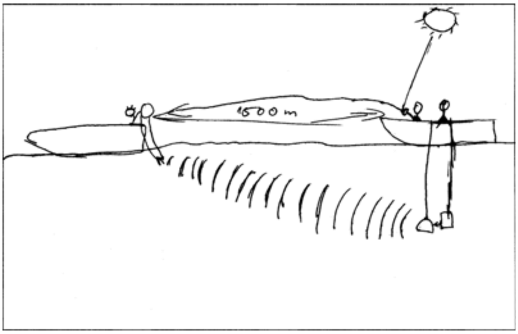


Fig. 65.11 Two experimenters in the first boat, one sending light signal by a mirror that reflects a ray from the sun

explicitly in the text. So, if some pupils omit in-text-mentioned persons in their drawings, then it is very likely that this situation model without persons will be found more frequently in pupil/student-generated drawings for the narrative given in the UK textbook (Johnson et al. 2001) that does not mention the persons who carried out the experiment.

65.5.1 Some Comments on Selected Pupils' Drawings

Pupils' sense making of the textbook verbal information about the Lake Geneva Experiment is a subtle process. It can be derived from pupils' drawings, which are their visual representations of the corresponding situation model.

In order to solve the problem how the two simultaneous events (i.e., hitting the bell and sending the light signal) were carried out, some pupils added the second experimenter in the first boat. One experimenter hits the bell and the other sends the light signal using a light source. Two different approaches were used to show the way the signal was sent. According to the first one, the signal was sent from a light source (Fig. 65.10). According to the second, the light signal consists of the solar light beam reflected by a mirror (Fig. 65.11).

A further difference appears in the second boat. Although in both cases the experimenter used the tube to receive the sound signal through the water, in the first case no

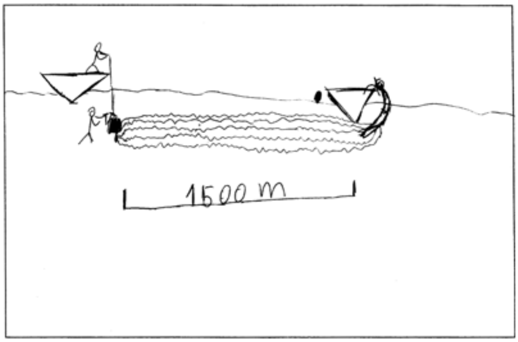


Fig. 65.12 One experimenter in the first boat and the second underwater

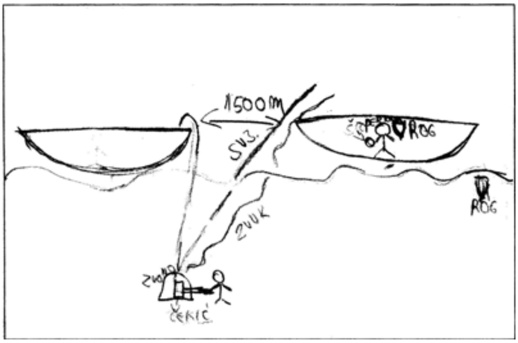


Fig. 65.13 An experimenter with two busy hands in the second boat

time-measuring device is presented, while in the second a watch is floating in the air near the experimenter. Obviously this pupil did not know the way the device operated.

Two experimenters are imagined in other drawings, too (Fig. 65.12). In the first boat one experimenter stands holding the rope with the bell, while the other experimenter is under the water hitting the bell. Obviously, for this pupil the only way to hit an underwater bell is to have somebody under the water to do it.

The same idea of hitting one underwater bell was adopted by another pupil (Fig. 65.13). Curiously, this pupil was able to imagine that the physicist in the second boat could use the right hand to hold the chronometer and the left hand to operate the tube.

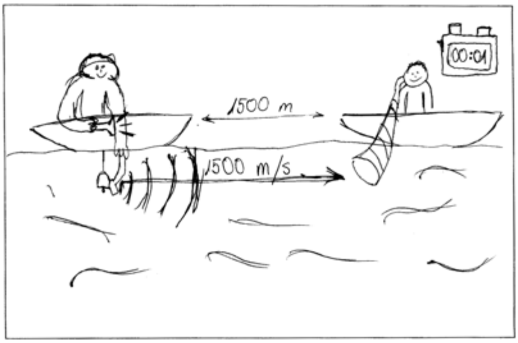
Another pupil applied the two-busy-hands idea for the experimenter in the first boat (Fig. 65.14). The first experimenter uses his right hand to send the light signal from a battery lamp and the left hand to hit the underwater bell by a hammer. Interestingly, this pupil did not apply the same idea for the second experimenter who holds the tube but not the digital chronometer.

One pupil drew both experimenters with two busy hands (Fig. 65.15). The experimenter in the first boat uses one hand to hit the underwater bell and the other hand to hold a mirror to send the light signal (in the form of reflected solar rays).

The experimenter in the second boat holds with both hands the timepiece, while the tube is attached to his left ear.

The mirror as light-sending device appeared in another drawing, too (Fig. 65.16). This pupil suggested a pendulum as time-measuring device.

Fig. 65.14 Experimenter with two busy hands in the first boat



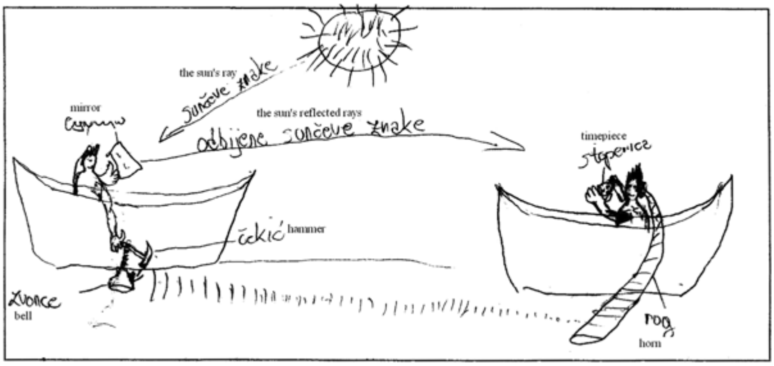


Fig. 65.15 Two experimenters with two busy hands

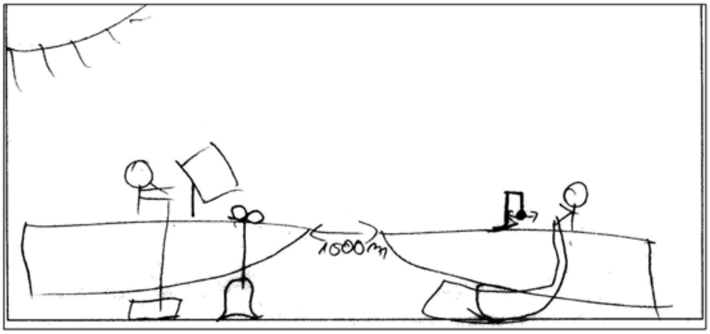


Fig. 65.16 Mirror as a light-sending device and a pendulum as time-measuring device

65.6 Conclusion

A great part of the historical information found in physics textbooks for primary school in Bosnia and Herzegovina is useless for learning about the nature of science because it is too short and rather incomplete. In the case of the Lake Geneva Experiment, a longer description of the historical episode was both historically erroneous and cognitively inadequate.

Cognitive adequacy was studied in relation to the textbook verbal description of the Lake Geneva Experiment aiming to measure the speed of sound in water. The task for the pupils was to make sense of the corresponding text by drawing the situation model concerning the specific experiment. In Kintsch's theory of text comprehension, the quality of the constructed situation model reveals the level of understanding.

Although 40 % of the pupils were able to draw an acceptable situation model with both light-sending and time-measuring devices that are absent in the textbook drawing, many pupils experienced difficulties in imagining how the experiment was done. Obviously, the text describing the experiment does not contain enough verbal clues to help these pupils construct a correct visual representation of the experimental situation. For them the textbook presentation of the experiment is incomplete and, in consequence, is not cognitively adequate.

In their sense-making efforts, some pupils suggested solutions (like underwater experimenter hitting the bell) that are erroneous. This fact shows that incomplete and superficial historical information is potentially misleading for pupils' learning.

Almost all pupils actively participated in the drawing activity, but very few provided written comments on the difficulties they experienced in thinking about how the experiment was done. The alarming absence of written pupils' notes about their thinking is very likely related to the classroom culture in which they rarely are asked to express what they think.

In the post-drawing discussion (with Z. H.), pupils commented that they enjoyed this novel activity (i.e., first draw the experimental situation and then compare their drawings with the textbook drawings) very much. It seems that most pupils prefer to talk about their ideas rather than to write about them, which is maybe a result of a rigid and more traditional education system in Bosnia and Herzegovina.

Up to date, this was the first study of the pupils' sense making of an incomplete textbook presentation of the Lake Geneva Experiment. Consequently, there are possibilities for future research. Some interesting questions are:

Would a "group drawing activity," following individual drawing attempts, improve the sense-making process of the same incomplete text?

Would a more complete verbal description of the historical episodes lead to better quality pupils' drawings?

Would impersonal account of the experiment, like the one in the UK textbook, be more difficult for pupils' drawing?

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Chapter 66
One Country, Two Systems: Nature of Science Education in Mainland China and Hong Kong

Siu Ling Wong, Zhi Hong Wan, and Ka Lok Cheng

66.1 Introduction

An understanding of NOS has been widely recognised as an essential component of scientific literacy and has been included as a curriculum goal in science curriculum standards documents in many developed regions of the Western world.[1] Driver, Leach, Millar and Scott (1996) have crystallised from the literature five arguments in support of developing students' NOS understandings:

1. Utilitarian – understanding NOS is necessary for making sense of the science and managing the technological objects and processes in everyday life.
2. Democratic – understanding NOS is necessary for making sense of socioscientific issues and participation in decision-making process.
3. Cultural – understanding NOS is necessary for appreciation of science as a major element of contemporary culture.
4. Moral – understanding NOS can help develop awareness of the norms of the scientific community that embodies moral commitments which are of general value.
5. Science learning – understanding NOS can support successful learning of science content.

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[1] See, for example, American Association for the Advancement of Science (AAAS) 1990; Council of Ministers of Education, Canada (CMEC) 1997; Department for Education (DfE), England 1995; and National Research Council (NRC) (1996).

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Although NOS has been one of the extensively researched areas in science education, there is not a unified way to define the term NOS in the literature. Some authors (Abd-El-Khalick and Lederman 2000; Lederman 2007) delimit NOS to aspects related to epistemology of science. In this chapter, we adopt a broader meaning of NOS in common with definitions adopted by Clough (2006), Irzik and Nola (2011), Osborne and his colleagues (2003) and Wong and Hodson (2009, 2010). The phrase NOS used in their work encompasses the nature of scientific inquiry, the nature of the scientific knowledge it generates, how scientists work as a social group and how science impacts, and is impacted by, the social context in which it is located.

Science education in both the mainland China and Hong Kong has undergone major curriculum reform since the beginning of the twenty-first century. One of the common new aims introduced in curriculum standards documents is the development of students' appreciation of nature of science (NOS).

Prompted by the soaring economy in recent years, which has brought tremendous changes in people's lives, the mainland Chinese government started to look for strategies to sustain long-term development of the country. These strategies include reforming education that can nurture and prepare the future generations for its development. Within science education in mainland China, there is a transition from a more elite to a more 'science for all' curriculum with an emphasis on the promotion of scientific literacy (Wei and Thomas 2005). NOS has hence started to become an important topic in some science curriculum reform documents (e.g. Ministry of Education [MOE] 2001a, b), Chinese academic articles,[2] as well as textbooks for training science teachers (e.g. Liu 2004; Yu 2002; Zhang 2004).

Science education in Hong Kong has also undergone considerable changes since the implementation of the revised junior secondary science curriculum (grades 7–9) (Curriculum Development Council [CDC] 1998). It was the first local science curriculum that embraced certain NOS features, e.g. being 'able to appreciate and understand the evolutionary nature of scientific knowledge' (CDC 1998, p. 3) was stated as one of its broad curriculum aims. In the first topic, 'What is science?', teachers are expected to discuss with students some features about science, e.g. its scope and limitations and some typical features about scientific investigations, e.g. fair testing, control of variables, predictions, hypothesis, inferences and conclusions. Such an emphasis on NOS was reinforced in the revised secondary 4 and 5 (grades 10 and 11) physics, chemistry and biology curricula (CDC 2002). Scientific investigation continued to be an important component, while the scope of NOS was slightly extended to include recognition of the usefulness and limitations of science as well as the interactions between science, technology and society (STS). In the recently implemented senior secondary curricula of the science subjects (CDC-HKEAA 2007), there is a further leap forward along the direction of earlier curriculum reforms in the curriculum and assessment guides. The importance of

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[2] See, for example, Chen and Pang (2005), Liang (2007), Xiang (2002), and Yuan (2009).

promoting students' understanding of NOS is explicitly spelt out together with its perceived benefits to students.

Although understanding of NOS has become a key curriculum aim in the science curriculums in both mainland China and Hong Kong, under the policy of the 'One Country, Two Systems', Hong Kong has retained its autonomy to decide on its own policies. There have been some distinctive differences of NOS education in both places as reflected in the (1) official curriculums, (2) textbooks, (3) teacher training and (4) school teachers' implementation of NOS teaching. This chapter provides an overview of the situations about NOS education in both places for these four areas.

66.2 NOS as Portrayed in Official Science Curricula

In a recent study, Cheng and Wong (in print) have examined the NOS ideas included in the two recent official senior physics curriculum documents used in mainland China (MOE 2004, thereafter known as '*CHN-Standards*') and Hong Kong (CDC-HKEAA 2007, '*HK-Guide*'). Ten NOS ideas are identified as listed below:

1. Laws as generalisations and theories as explanations of the generalisations
2. Creative elements of the scientific processes
3. Tentative and developmental nature of science
4. Distinction and relationship between science and technology
5. Theory-laden nature of scientific processes
6. Empirical nature of scientific knowledge
7. Different ways of performing scientific investigations
8. Interactions between science, technology and the society
9. Moral and ethical dimensions of science
10. Scientists as a community

Among them, some are similarly represented in both Hong Kong and the mainland China, including 'Laws as generalisations and theories as explanations of the generalisations', 'Tentative and developmental nature of science', 'Empirical nature of scientific knowledge' and 'Scientists as a community'. However, some of these NOS ideas, including 'Different ways of performing scientific investigations', 'Interactions between science, technology and the society' and 'Moral and ethical dimensions of science', are presented with significant differences.

66.2.1 Methods of Scientific Investigations

There is a dedicated chapter on scientific investigations in *CHN-Standards* in which the 'components of scientific investigations' are listed in a table as shown in Table 66.1. The seven components are stunningly similar to *the* stepwise scientific method as one of the myths about NOS highlighted by McComas (1998).

Table 66.1 Components of scientific investigations as presented in *CHN-Standards* (pp. 10–11)

Components of scientific investigations	Basic skill requirements for scientific inquiries and physics experiments
Question formulation	Able to discover physics-related problems Express these problems clearly as physics problems Aware of the significance of problem discovery and question formulation
Speculation and hypothesis formation	Propose problem-solving methods and solutions to problems Predict the results of physics experiments Aware of the importance of speculation and hypothesis
Experiment planning and design	Develop plan according to the experimental objectives and conditions Attempt to select the appropriate experimental methods, set-ups and instruments Consider the experimental variables and their control Aware of the role of planning
Experimentation and data collection	Collect data using a variety of methods Perform experiments according to guidelines and able to use common instruments Faithful recording of experimental data and aware of the meaning of the duplicated collection of experimental data Being safety-conscious Aware of the importance of objective collection of experimental data
Analysis and reasoning	Analysis of experimental data Attempt to develop conclusion according to the observations and data Explain and describe the experimental data Aware of the importance of analysis and reasoning to experiments
Evaluation	Attempt to analyse the differences between hypotheses and experimental results Attend to the unresolved issues in the inquiries and discover new problems Improve the inquiry plan with reference to the experience gained Aware of the significance of evaluation
Exchange and co-operation	Able to write reports for the experimental inquiries Upholding principles while respecting others during co-operation Be co-operative Aware of the importance of exchange and co-operation

In the *HK-Guide*, 'scientific investigation' is a subsection under Skills and Processes,[3] where the intended learning targets that could be acquired through conducting scientific investigations are listed. Students are expected to:

- Ask relevant questions
- Propose hypotheses for scientific phenomena and devise methods to test them
- Identify dependent and independent variables in investigations
- Devise plans and procedures to carry out investigations
- Select appropriate methods and apparatus to carry out investigations
- Observe and record experimental observations accurately and honestly
- Organise and analyse data and infer from observations and experimental results
- Use graphical techniques appropriately to display experimental results and to convey concepts
- Produce reports on investigations, draw conclusions and make further predictions
- Evaluate experimental results and identify factors affecting their quality and reliability
- Propose plans for further investigations, if appropriate

(HK-Guide, pp. 9–10)

It is noteworthy that among all nine subsections under Skills and Processes, 'practical work' shares a few similar learning targets as 'scientific investigations', for example, students are expected to:

- Devise and plan experiments
- Select appropriate apparatus and materials for an experiment
- Interpret observations and experimental data
- Evaluate experimental methods and suggest possible improvements

(HK-Guide, p. 10)

By listing the expected learning targets related to Skills and Processes expected to be achieved through scientific investigation instead of spelling out the 'Components' of Scientific Investigations as presented in *CHN-Standards*, the *HK-Guide* might give a lesser impression of a rigid stepwise method of doing scientific investigations.

66.2.2 Interactions Between Science, Technology and Society

While the specifications on the discussion of the positive aspect of the technological applications of science are found in both documents as expected, *CHN-Standards* attends to the societal development brought by technological advances to a larger

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[3] The learning targets of the Hong Kong physics curriculum are categorised into three domains: Knowledge and Understanding, Skills and Processes and Values and Attitudes.

extent. Students are required to appreciate 'the roles of the widespread use of heat engines in bringing about the changes towards science, *social development and the mode of living*'. (p. 22, emphasis added), while the specification in the *HK-Guide* requires students to understand 'how major breakthroughs in scientific and technological development that eventually affect society are associated with new understanding of fundamental physics' (p. 49).

The *HK-Guide* also pays more attention to the controversies that can be caused by new technologies, for example, in the topic of Wave Motion, students are expected to develop understanding of the 'controversial issues about the effects of microwave radiation on the health of the general public through the use of mobile phones' (p. 38). Also, in the topic of Radioactivity and Nuclear Energy, students are 'to be aware of different points of view in society on controversial issues and appreciate the need to respect others' points of view even when disagreeing; and to adopt a scientific attitude when facing controversial issues, such as the use of nuclear energy' (p. 51).

On the other hand, the *CHN-Standards* only generally states that students should be 'aware of the social problems that are brought about by the technological applications of Physics' (p. 2); it is less emphasised on, if not silent, about controversial issues related to use of technologies. For example, in the topics of Energy Sources and Development of Society, it is suggested that students 'investigate the common pollutants causing air pollution' (p. 23) and 'understand the development and application of nuclear technology as well as its outlook' (p. 23). Yet contested views about the use of nuclear energy are not brought up.

The lack of suggested learning and teaching activities for discussion of controversial socioscientific issues in the *CHN-Standards* is strikingly consistent with the absence of the democratic argument as a reason for teaching NOS as stated by the Chinese science teacher educators reported by Wan and colleagues (2011). As the authors said,

> [T]he absence may be explained in terms of the political context in China… a socialist country governed by Chinese Communist Party. In such a less decentralized system, general public has relatively little voice in the public decision on social issues. (p. 1118)

66.2.3 Moral and Ethical Dimensions of Science

The only relevant content related to the moral and ethical dimensions of science in the *CHN-Standards* is about the positive image of scientists. The *CHN-Standards* suggests textbooks to 'use vivid information to exhibit their scientific spirit and their determined devotion to science' (p. 58). Scientists are to be honoured for their respectable character and selfless commitment to the development of science. The *CHN-Standards* also explicitly spells out the intention of using examples to illustrate such scientific spirit in order facilitate character building of learners.

In comparison, the perspective adopted by *HK-Guide* is more balanced and reflective. Students are suggested to discuss 'the roles and responsibility of scientists and the related ethics in releasing the power of nature' (p. 52) and address to the 'moral issues of using various mass destruction weapons in war' (p. 52). Unlike *CHN-Standards*, scientists as portrayed in the *HK-Guide* are not simply 'heroes' to be appreciated; the moral and ethical consequences of the technologies resulted from their endeavour are to be examined.

66.3 NOS as Portrayed in School Science Textbooks

Two sets of corresponding physics textbooks from each city, including the one published by People's Education Press (Centre for Research and Development on Physics Curriculum Resources of PEP 2004, 'PEP') and the one by Guangdong Education Press (Editorial Group for Physics Textbooks, Guangdong 2004, 'GEP') from Guangzhou, and the set published by Oxford University Press (Wong and Pang 2009, 'OUP') and by Longman (Tong et al. 2009, 'Longman') in Hong Kong, were studied.

Almost all NOS ideas that are commonly found in the official curriculums in the West (McComas and Olson 1998) are embedded in the textbooks used in both Hong Kong and the mainland China. It seems that the absence of corresponding NOS ideas in the official curriculums has not resulted in their absence from the textbooks. For instance, the text segments that could be deployed to exhibit the 'theory-laden nature of scientific processes', absent in *CHN-Standards*, could be found in the historical episodes included in the textbooks used in the mainland China. Similarly, while the 'creative elements of the scientific processes' are not included in *HK-Guide*, the use of analogical thinking in scientific process could be found in a small dose in the textbooks of Hong Kong. Considerable differences of NOS ideas presented in the textbooks of both sites are again from the three aspects described above.

66.3.1 Methods of Scientific Investigations

The implied message on the universality of scientific method is translated into concrete form in the textbooks of the mainland China. In PEP, a shortened sequence of the processes listed as 'key components of scientific investigation' (pp. 10–11, *CHN-Standards*) is diagrammatically presented as the common method to be used in science (Fig. 66.1). To illustrate such a sequence, the work of Galileo in the study of free-falling object is reconstructed and 'moulded' into the fixed sequence of steps shown in the diagram.

However, the textbooks in Hong Kong, unlike their mainland counterpart, do not produce a similar list in their texts for a less than impressive reason though: Both OUP and Longman mostly consist of 'cookbook'-type practical activities with the key purposes of facilitating students to learn the relevant target concepts and to practise experimental skills, which will be examined through written and

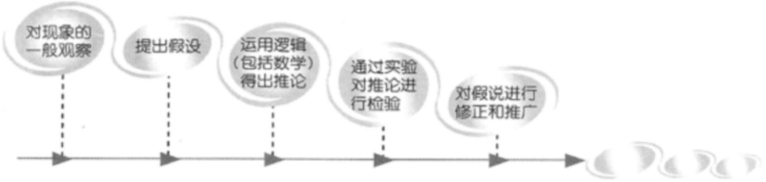

Fig. 66.1 Picture in one of the textbooks used in the mainland China (PEP 2004, Physics-1 p. 48) showing the steps of 'the scientific method' (The phrases in the picture, from left to right, mean 'General observation of phenomena', 'Hypothesizing', 'Obtaining corollary using logic (including mathematics)', 'Evaluation of the corollary through experiment' and 'Amendment and extension of the hypothesis')

practical examinations, respectively. The full detailed procedures of each practical activity are provided in the experimental workbooks, whereas the textbooks only provide an abridge version for reminding students the key features of the practical activity. The practical activities are more like heavily guided scientific investigations. Students can perhaps tell from the variation of the procedures of each practical activity that scientific investigations do not consist of a fixed set of stepwise procedures.

66.3.2 Interactions Between Science, Technology and the Society

The focus on the role of scientific and technological advances to the societal development in *CHN-Standards* is translated into textbooks in the mainland China. For example, the societal impact of the Industrial Revolution including that 'the venue of production changed from dispersed family production [houses] for agriculture and handcrafts to factories for centralized production', 'self-sufficient natural economy had evolved into market economy in which production and consumption are separated' and 'the development of cities facilitated the advancements of science, technology, education and cultural industries. Human society [were going] into the era of industrial civilization' (PEP 2004, Elective 1–2, p. 77) can be found in the textbooks.

The particular attention paid to the statements on 'the rise of manufacturing and service industries' and 'rise of market economy and capitalism' may be the result of the influence of the Marxist idea on historical periodisation, as similar influence of Marxism on the science teacher educators in the mainland China can also be found in Wan and colleagues (2012) and in the previous section of this chapter.

While textbooks are required to cover on the societal problems brought about by the products of science, the negative consequences of these applications are downplayed in PEP. For instance, safety problems stemmed from the use of nuclear energy are simply stated to be issues that 'are continuously being attended to'

(PEP 2004, Elective 1–1, p. 58), while two major nuclear meltdowns (the Three Mile Island accident and Chernobyl disaster) are just touched on (pp. 59–60) without any discussion of the related controversy.

However, GEP is not equally silent on socioscientific controversies, for instance, in the nuclear pollution problems brought by the Chernobyl disaster and the worries of the people on the use of nuclear power, which are natural results, are being mentioned (GEP 2004, Elective 2–3, p. 89). However, it is still attempting to contain students' worries by providing information like 'the nuclear reactors use low-enriched uranium… As such, reactors will not explode like nuclear bombs.' (GEP 2004, Elective 1–2, p. 50) to ensure students will not overreact towards the possible nuclear hazards.

On the other hand, for the societal implications of science and technology, the controversy about the use of nuclear energy is included in the OUP, and this corresponds well to the specifications in *HK-Guide*. In its discussion, the authors deploy a cartoon showing two demonstrations organised by pro- and anti-nuclear camps to represent the conflicting views presented on both sides (Radioactivity p. 90). Besides being told that there may be controversies, students are guided to study them. For instance, in the discussion of the possible harmful effects brought by the overhead power cables, students are required 'to find out … action taken by pressure groups and the response of electricity companies' (Electricity p. 280). The socio-scientific conflicts among different stakeholders and groups are being investigated.

However, in *Longman*, the impacts of science and technology on the society are superficially covered. Moreover, socioscientific controversies are mostly replaced by scientific findings on the possible health effects, as in the case of the overhead power cables. Socioscientific controversies are reduced to scientific colloquia:

> Some researches indicate that exposure to changing electric and magnetic fields from transmission lines may incur a number of health problems. These include leukaemia, cancer, miscarriage, clinical depression, etc. However, these conclusions are solely based on statistical studies … The detailed mechanism is still unclear. (*Longman* Vol. 4, p. 440)

66.3.3 Moral and Ethical Dimensions of Science

The particular specification on the need for the textbooks to portray scientists as good models of students results in the narratives in *PEP* that describe scientists as extraordinarily moral such as the despise of wealth and title as presented through the example of Faraday and having the 'courage' in making the difficult decision to suggest the use of atomic bombs (which is unlikely to be presented as such in the curriculum artifacts of the West):

> Some scientists, especially those escaped from the Fascist persecution, had a premonition about the threat of atomic bombs especially after they had heard that Germany had accelerated the research on chain reactions… On July 1939, nuclear physicist Szilard and others found Einstein and wished he could use his status to urge United States to produce atomic bombs before Germany had done so… (PEP 2004, Elective 3–5, pp. 84, 85)

Similar narratives of scientists' advocacy on the use of atomic bombs to counter the possible threats can be found in the chapter of atomic physics in *GEP*. However, a more reflective stance is taken. The text initiates a discussion on whether scientists should be free from the moral consequences of their work:

> Should people develop nuclear technology if both the pros and cons are taken into account? Some say scientists should care about science *per se*, while the impacts of science and technology to the society should be under the care of sociologists. Do you agree? (*GEP* Elective 3–5 p. 88)

The textbooks in Hong Kong also invite students to reflect on the moral responsibility of scientists. The deaths, injuries and sicknesses resulted from the use of atomic bombs in World War II are mentioned, and rhetoric that attempts to identify scientists' responsibility of using atomic weapons was used (*OUP*, Radioactivity p. 96).

In *Longman*, the moral and ethical aspects are pointed out but not discussed in depth. For example, while 'international race of nano-weapons' and the 'technology of changing and even constructing DNA' are said to cause much impact on ethical values (Atomic World, p. 149) and nuclear energy is said to be able to 'destroy our civilization if it is misused' (Radioactivity, p. 108), no further discussion is following these brief mentions.

From the comparison of the official curricula in both sites, it can be seen that there are differences between mainland China and Hong Kong regarding their inclusion of NOS ideas in the official curricula. There are also significant differences in terms of the inclusion and the focus of the NOS ideas in the textbooks. It is obvious that some messages (overt and covert) in the official curricula could (and sometimes fail to) influence the corresponding textbooks. Given the important status of textbooks in the science classrooms in both mainland China and Hong Kong, a follow-up study in identifying how other factors, on top of the official curricula, play their roles in shaping the NOS ideas found in the textbooks is being conducted.

66.4 Preparing Science Teachers to Teach NOS in Mainland China

Although NOS has appeared in the revised science curriculum documents in mainland China, the training is mostly dependent on the initiative of science teacher educators in Normal (teacher training) Universities. There are no large-scale teacher professional development projects funded by the government in developing in-service teachers to achieve a critical number of teachers in implementing the new curriculum goals. It appears that the current priority for science education reform of the Chinese government is more concerned with promoting inquiry-based science teaching and learning. Nevertheless, as reported in recent studies (Wan 2010; Wan et al. 2011, 2012), there are a number of Chinese science teacher educators teaching NOS to prospective science teachers in their courses for the bachelor degree of science education.

The study by Wan and colleagues (2012) revealed the influence of Marxism on these educators' conceptions. Although, during the interviews in this study, the factors influencing Chinese science teacher educators' views of NOS had not been intentionally asked, three science teacher educators explicitly stated that their NOS views are influenced by Marxism, especially dialectical materialism, which had been taught since their school time:

> My understanding of NOS is influenced by my early education of dialectical materialism. I had been taught of Marxism when I was in the school. It is common for the people grown up under the Red Flag[4] like me. Although it is too politicized in China, I feel most of its arguments are right, especially for those on natural philosophy…When I started to read the literature on NOS, I made use of my knowledge of dialectical materialism to understand it. (Wan et al. 2012, p. 16)

In addition to such general arguments, the influence of Marxism on Chinese science teacher educators' conceptions in NOS content to be taught is reflected in some specific aspects of the findings in the study.

66.4.1 Realist Views of Mind and Natural World

It is rather rare to find realist statements in the Western literature on NOS instruction. Even when it is found in *Science for All American* (American Association for the Advancement of Science [AAAS], 1990), one of few found by the authors, the tone adopted to present it is very assumptive:

> The world is understandable…Science *presume*s that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study. Scientists believe that through the use of the intellect, and with the aid of instruments that extend the sense, people can discover patterns in all of nature. … Scientist also *assumes* that the universe is, as its name implies, a vast single system in which the basic rules are everywhere the same. Knowledge gained from studying one part of the universe is applicable to the parts. (AAAS 1990, p. 2, authors' emphasis)

Wan et al. (2012) found that realist understandings of mind and natural world were considered by more than half of Chinese science teacher educators as scientific worldview and suggested by them as NOS content to be taught:

> One aspect of NOS is some basic thoughts guiding scientific investigation, including basic understanding of matter, motion…These scientific worldviews included understandings that … *the world is material*, all matters in world are *connected*, such connections are universal, *matters are in constant motion*, there are rules underlying such motion, and all these connection and rules are knowable to human being. (p. 14)

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[4] Red Flag means the flag of Chinese communist party. Actually, red is the colour of all communist parties. The people grown up under the Red Flag refer to the people that are under influence of communist party.

The statement cited above reflects several core elaborated realist arguments:

(a) The existence of an external world that is independent of the observer
(b) The universality and constancy of connection in the world
(c) The possibility of our mind to know the external world and connections within it

These three statements are the prerequisites to arrive at the final and core argument of realism, i.e. the existence of the corresponding relationship between scientific knowledge and natural world. Without the existence of an independent material world, it is meaningless to discuss the relationship between scientific knowledge and natural world. The major form of the scientific knowledge is the universal and constant connection between variables, so if it is believed that there is no such universal and constant connection existing in the real world, the natural conclusion will be that such corresponding relationship cannot possibly exist between scientific knowledge and natural world. Even with the conditions of (a) and (b), if we do not admit that we can, through the use of the intellect and with the aid of instruments that extend the sense, discover such connection in the world, such a corresponding relationship is still problematic.

Indeed the choice of the words and the tone adopted by the Chinese science teacher educators are rather affirmative. This tendency is consistent with Marxist tradition, where realist epistemology is believed by Marxists as the right philosophy or worldview to guide scientists. Actually, on the basis of their materialist ontology, Marxists hold the realist epistemology (Curtis 1970; Farr 1991; Murray 1990), which admits the knowability of the material world. In Stalin's formulation: 'The world and all its laws are fully knowable … there are no things in the world which are unknowable, but only things which are as yet not known' (Stalin 1985, p. 18). He was elaborating Engel's contention that:

> natural scientists may adopt whatever attitude they please, they will still be under the domination of philosophy of science. It is only a question whether they want to be dominated by a bad, fashionable philosophy or by a form of theoretical thought with rest on acquaintance with the history of thought and its achievement. (Engels 1976, p. 558)

For Marxists, such theoretical thought includes the realist epistemology described before.

Although the core meanings of the excerpts are similar to the popular realist statements, there is still some difference as reflected in the emphasised words. First, emphasising that the world is material may reflect a materialist tendency, which is not necessarily held by realists – many realists grant the existence of nonmaterial things (fields, etc.). Second, the concepts of connection and change, which are not commonly included in the popular realist statements, are obviously emphasised in the above excerpts. However, the concepts of connection and change are the basic points of dialectics in Marxism, so some popular Chinese textbooks of Marxism integrate them with materialism and realist arguments to make a summary of Marxism principles. Hence although the possibility may not be totally excluded that the appearance of this NOS element and its high frequency is the result of the influence of other philosophical theories, the above clues indicate that it might more probably be the outcome of the influence of Marxism.

66.4.2 Truth-Approaching Nature of Scientific Knowledge and Science as the Pursuit of Truth

There are also other two realist NOS elements found in the study, i.e. truth-approaching nature of scientific knowledge and science as the pursuit of truth, whose meanings are very similar. The first believes that 'scientific knowledge as *relative truth*…Although it may never arrive at the state of *absolute truth*, its development is a process of continuous progression towards the truth in the objective world' (Wan et al. 2012, p. 16). The idea that science cannot obtain final truth but nevertheless can progressively obtain better approximations to the truth was enunciated by Karl Popper and called 'verisimilitude'. At the same time, the second argues that 'the goal of scientific investigation is to pursue truth, to reflect the real picture of the objective world…Science is unlike art. Art aims to pursue aesthetics, which allows departure from the fact and reality. But science investigation does not allow it' (Wan et al. 2012, p. 15). Although they were not suggested as frequently as the scientific worldview, if we count together the number of educators who have suggested them, there will be a total of ten. However, these two elements are hardly found in most recent science education curriculum in the West and academic publications on NOS studies. Such a feature in Chinese educators' conception is consistent with Marxist realist epistemology introduced before.

It can be also found that the terms *relative truth* and *absolute truth* were used as a pair by Chinese science teacher educators to describe truth-approaching nature of scientific knowledge. Truth is an important issue in many other branches of philosophy, but it is uncommon to couple these two terms to discuss the nature of knowledge in their literature. On the contrary, since being used by Lenin in his work *Materialism and Empirio-criticism* (Lenin 1977), this pair of terms has been popularly used among Marxists:

> Human thought then by its nature is capable of giving, and does give, absolute truth, which is compounded of a sum-total of relative truths. Each step in the development of science adds new grains to the sum of absolute truth, but the limits of the truth of each scientific proposition are relative, now expanding, now shrinking with the growth of knowledge. (Lenin 1977, p. 135)

Similar statements can be found in almost all the Chinese books on Marxism. Therefore, the appearance of this pair of terms is another indication of the influence of Marxism on Chinese science teacher educators' conception.

66.4.3 Logical Thinking in Scientific Investigation

Logical thinking in scientific investigation was considered by 15 Chinese science teacher educators as important for a scientific worldview and suggested by them as NOS content to be taught. It was depicted by a chemistry teacher educator:

> Induction and deduction are both important logical methods in scientific investigation. Deduction is from the general theory or concepts to the specific conclusion or facts…On the contrary, induction is the reasoning from the specific conclusion or facts to the general theory or concepts…I feel human understanding of the world is an endless process from the specific to the general, and then to higher level of the specific. It is a spiral process. (Wan et al. 2012, p. 12)

On the contrary, this NOS element is uncommon in the Western literature on NOS instruction. And even it is found, little elaboration is made. The caution about elaborating this element in the West may be due to the controversies between inductivism and deductivism in the philosophy of science. However, as reflected in the data, Chinese science teacher educators did not seem to concern conflicts between them. On the contrary, deduction and induction were considered as something like a unity of the opposite. This point is rather similar to Marxist view. ‘Induction and deduction belong together…Instead of one-sidedly raising one to the heavens at the cost of the other, one should seek to apply each of them in its place, and that each completes the others’ (Engels 1976, p. 519).

66.4.4 Empirical Basis of Scientific Investigation, General Process of Scientific Investigation and Progressive Nature of Scientific Knowledge

As indicated in the paper, except realist understanding of mind and natural world, the other four NOS elements suggested by more than a half of the educators in this study as NOS content to be taught are all NOS elements related to empiricism, i.e. empirical basis of scientific investigation, logics in scientific investigation, general process of scientific investigation and progressive nature of scientific knowledge.

The empirical basis of scientific investigation emphasises the role played by observation and experiment in the process of scientific investigation. As stated by one educator, ‘empirical method is one of major features of scientific investigation since whether the results or arguments in science will be accepted or not will depend on the result of testing through observation or experiment’ (Wan et al. 2012, p. 10). The origin of the empirical nature of scientific investigation can be traced back to the empiricism in the philosophy of science, emphasising the crucial role of human senses in the generation of scientific knowledge. Just relying on the empirical data cannot give a full explanation of the development of the scientific knowledge. In order to establish the validity of the scientific knowledge, it is necessary to provide a method to bridge between empirical data and scientific knowledge. The empiricist philosophers of science suggested that logic would serve such a purpose. Therefore, logics in the scientific investigation are also an empiricist NOS element.

General process of scientific investigation means a set of elements of conducting scientific research. It usually ‘starts with a question, proceeds then with proposing some hypotheses or arguments to the question, testing such hypotheses or arguments through observation or experiment, drawing some conclusions and at the end communicating such conclusion so as to convince people of the conclusions’ (Wan et al. 2012, p. 13). The discussion on general process or method of science can find its origin in empiricist philosophy of science. Both inductive empiricists and deductive empiricists were concerned to provide a scientific method. For inductive empiricists like Francis Bacon (1562–1626), the scientific method generally consists of four steps: observation and experimentation, classification, generalisation and testing. But deductive empiricists, like Karl Popper (1902–1994), think that the only logic that science requires is deductive logic. The method of science advocated by Popper is known as hypothetic-deductive method, which consists of the following steps (detailed description of Popper’s methodology is given in Popper 1959):

(a) Formulate a hypothesis (H).
(b) Deduce an empirical consequence (C) from H.
(c) Test C directly.
(d) If C is acceptable under the scrutiny of sense experience, return to step (b) and obtain another C for the further testing of H.
(e) If, on the other hand, C is rejected, H should be rejected as a consequence of modus tollens.

Regardless their differences in the specific steps included in the process of scientific investigation, the inductive empiricists and deductive empiricists are common in believing that there should be a general process of scientific investigation.

Chinese science teacher educators argued that ‘science accumulates and progresses in its own self-correcting process. Most of other subjects do not have such a feature…The typical example is art. If anyone wants to revise de Vinci’s Mona Lisa, who can produce a one better than the original?’ (Wan et al. 2012, p. 14). Stating the development of scientific knowledge is an accumulative or a progressive process is a typical stance originating in empiricism philosophy of science. The empiricists commonly conceive the development of science as a process that the replaced theories are reduced (and thus absorbed) into the replacing theory. For example, they take Newton’s theory as being reduced to Einstein’s theory. On the basis of such kind of understanding, the development of scientific knowledge is naturally considered as cumulative and continuous. In contrast with the understanding of the development of scientific knowledge as a process of replacement and absorption, it was thought by Kuhn (1970) that *scientific revolutions* also exist in the development of scientific knowledge, during which a process of replacement and displacement happens, rather than replacement and absorption.

Some interview data indicated that the popularity of Chinese science teacher educators’ inclusion of empiricist NOS elements in their instruction may also be partly caused by Marxism. As explicitly stated by two educators during the interview:

> I believed dialectical materialism since I was young…I think it’s consistent with the realist and empiricist philosophy of science, so I choose to focus on these classical NOS elements in my teaching. (Wan et al. 2012, p. 18)

Practice is the crucial concept in Marxism, which is considered as the starting point, the basis, the criterion and even the purpose of all knowledge (Mao 1986).[5] As stated by Marx (1976), 'the question whether objective truth can be attributed to human thinking is not a question of theory but is a *practical* question … the dispute over the reality or non-reality of thinking that is isolated from *practice* is a purely scholastic question' (p. 3) (authors' emphasis). Here, *practice*, in plain words, means the activity of applying mind into reality. For example, when some hypotheses are generated during the process of doing scientific investigation, we need to predict what phenomena are to be observed if the hypotheses are correct. On the basis of such predictions, appropriate scientific experiments are designed. The results of the scientific experiments are the evidence of supporting or refuting such hypotheses. The action of designing and doing experiments is a process of applying ideas into reality, so it is a kind of *practice*.

During the process of teaching, we use a certain kind of educational theory to guide the design of our teaching activities. If we find that students learn better, such a result is the evidence to support this educational theory. This kind of teaching activity is also *practice*. In fact, during the process of applying our mind into reality, we can, at the same time, get the responses from the reality through our sense experience, which can be not only empirical evidence to support or refute our mind, but the resources of generating new ideas. It is not difficult to note that empirical evidence, which is emphasised by empiricist epistemology, is implicitly integrated into the concept of *practice* in Marxism. Thus it is believed that Marxist philosophy, to a large extent, is consistent with empiricist epistemology (Creaven 2001). Of course, except the logics in scientific investigation, no addition clue in the wording can be found for the other three NOS elements to link their origin of Marxism. They may be influenced by Marxism in a more indirect manner.

Unlike the West where most science teacher educators focus on the contemporary views of NOS, most Chinese science teacher educators participated in Wan's (2010) study tend to put greater emphasis on realist views of science, though many of them are also knowledgeable about the contemporary views of NOS.

66.5 Preparing Science Teachers to Teach NOS in Hong Kong

In stark contrast to mainland China, Hong Kong science teacher educators have received continuous funding and support from the Education Bureau (EDB) of the Hong Kong Government in conducting a series of teacher professional development (TPD) and research projects to prepare teachers to develop students' understanding of NOS. As said in the previous section, science teacher educators and teachers in

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[5] Mao Zedong first elaborates the concept of practice in his classic article 'On Practice: on the relation between knowledge and practice, between knowing and doing' written in July 1937, which is collected in various versions of Selected Works of Mao Zedong. The specific article cited here is this one included in Mao (1986).

mainland China put the highest priority in practising inquiry-based teaching and learning in science classrooms. Most teacher seminars and national teaching competitions are mainly centred at promoting teachers' pedagogical skills in carrying out inquiry-based teaching and learning. Most resources are allocated to equip the school laboratories with modern apparatus and equipment for conducting inquiry activities. It may be a reason why there have been no reports about the regular practice of teaching NOS in school classrooms in mainland China.

For Hong Kong, learning science through laboratory-based activities has been common at school level (albeit the activities are often carried out through 'cookbook' approach). School-based assessment on practical work or investigative studies have also been implemented in the 1980s starting from chemistry, followed by biology in the 1990s and physics in the 2000s. The emphasis on hands-on practical activities in school science was largely a result of the influence of the British educational system in which the Nuffield Curriculums had been influential since the 1970s until 2012 when the Hong Kong Advanced Level Examination[6] was replaced by the Hong Kong Diploma of Secondary Education Examination. Thus the school laboratories are mostly well equipped already. For the recent reform in science education which aims to promote students' scientific literacy, NOS turns out to be an area that most science teachers are unfamiliar with and hence EDB sees an urgent need to provide funding in support of TPD projects along the direction of the new curricular goals.

In this section, we review the decade of efforts by the group of science educators of the University of Hong Kong (HKU) in promoting teachers' understanding of NOS and pedagogical skills in implementing NOS teaching in their classrooms. Our sharing will situate in the 8-year experience in learning to teach NOS of a physics teacher, Henry. Henry first started learning about some general NOS ideas since 2003 when he studied for his Postgraduate Diploma in Education (PGDE) course, major in physics at HKU. Through the reflection on Henry's learning journey based on the detailed records of his learning and our TPD programs, we highlight some critical stages of his learning journey. We hope our in-depth reflection will provide insights on the design of effective TPD for similar future initiatives.

66.5.1 A Decade of Effort in Preparing Teachers for the Reformed Curricular Goals

In response to the curriculum reform in Hong Kong, science teacher educators have initiated a series of research and TPD projects since early 2000 to support pre-service and in-service science teachers to teach NOS. We are cognisant of the

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[6] The examination was similar to the British General Certificate of Education Advanced Level Examination except that it was much more competitive due to the very low university admission rate in Hong Kong.

numerous problems and challenges identified in the West. Lederman's (1992) critical review came to a disappointing conclusion that both students and science teachers have inadequate understanding of NOS (Lederman 1992). There is however empirical evidence that can inform ways to improve NOS understandings. Explicit and reflective approaches and strategies using historical account of scientific development and/or through scientific inquiry in teaching NOS can support learner development of sophisticated NOS ideas (Abd-El-Khalick and Lederman 2000; Khishfe and Abd-El-Khalick 2002). Yet, teachers with good understanding in NOS still face many constraints including concerns for student abilities and motivation (Abd-El-Khalick et al. 1998; Brickhouse and Bodner 1992), lack of pedagogical skills in teaching NOS (Schwartz and Lederman 2002) and lack of teaching resources (Bianchini et al. 2003) particularly those in local contexts and language (Tsai 2001). Effective NOS teaching also depends on teachers' belief in the importance of teaching NOS (Lederman 1999; Tobin and McRobbie 1997) and their conception of appropriate learning goals and teaching role (Bartholomew et al. 2004).

66.5.1.1 Inadequate NOS Understanding: Missing the Target NOS

In support of the implementation of the revised junior secondary science curriculum, Tao, Yung, Wong, Or and Wong (2000) wrote a new series of textbooks which included four science stories on penicillin, smallpox, Newton's Law of Universal Gravitation and the treatment of stomach ulcers. Although these stories were designed such that teachers could highlight the NOS aspects through an explicit approach (Abd-El-Khalick and Lederman 2000), it was found that students' learning of NOS based on these stories was disappointing (Tao 2003). In fact many teachers, including Henry, considered the stories good for arousing student interest without attending to the primary purpose of teaching relevant NOS idea, as shared by a junior science teacher who came to realise his oversight after he attended the NOS sessions in our PGDE courses in early 2000s:

> I found the story on stomach ulcers very interesting....Marshall tested his hypothesis by trialing out himself....Students all enjoyed the story… I only realise now that there are deeper meanings behind the story and other important learning outcomes to be achieved through it and other stories.

We learnt from this experience that availability of teaching resources would not by itself result in teachers making use of the materials to teach NOS unless teachers had the ability to understand and appreciate the intended learning outcomes of the instructional materials. It is likely that they would overlook the targeted learning objectives (McComas 2008) and cling onto the parts which were more appealing to them (dramatic stories which promote students' interest). We also reckoned that there were some inadequacies of these relatively 'old' stories. Teachers and students expressed that though these stories aroused their interests, they happened quite a while ago. Those who did not have the historical and cultural backgrounds of the scientific discoveries and inventions would fail to develop an in-depth understanding of, and hence appreciate, the thought processes of the scientists related to what they encountered at their time.

66.5.1.2 Effective Learning of NOS Contextualised in the SARS Story

In summer 2003, when the crisis due to the severe acute respiratory syndrome (SARS) in Hong Kong was coming to an end, we saw a golden opportunity to turn the crisis into a set of meaningful instructional resources which might help address the issues raised above. The SARS incident was a unique experience that everyone in Hong Kong had lived through and the memories of which would stay for years. At the beginning of the outbreak, the causative agent was not known, the pattern of spread was not identified, the number of infected cases was soaring, yet an effective treatment regimen was uncertain. It attracted the attention of the whole world as scientists worked indefatigably to understand the biology of the disease, develop new diagnostic tests and design new treatments. Extensive media coverage kept people up to date on the latest development of scientific knowledge generated from the scientific inquiry about the disease. As anticipated we identified many interesting aspects of NOS based on our interviews with key scientists who played an active role in the SARS research, analysis of media reports, documentaries and other literature published during and after the SARS epidemic.

The SARS incident illustrated vividly some NOS features advocated in the school science curriculum. They included the tentative nature of scientific knowledge, theory-laden observation and interpretation, multiplicity of approaches adopted in scientific inquiry, the interrelationship between science and technology and the nexus of science, politics, social and cultural practices. The incident also provided some insights into a number of NOS features less emphasised in the school curriculum. These features included the need to combine and coordinate expertise in a number of scientific fields, the intense competition between research groups (suspended during the SARS crisis), the significance of affective issues relating to intellectual honesty, the courage to challenge authority and the pressure of funding issues on the conduct of research. The details on how we made use of the news reports and documentaries on SARS, together with episodes from the scientists' interviews to explicitly teach the prominent features of NOS, can be found in Wong et al. (2009). Since January 2005, we have been using the SARS story in promoting understanding of NOS of hundreds of pre-service and in-service science teachers. The learning outcomes have been encouraging (Wong et al. 2008).

66.5.1.3 Integrating NOS Teaching into Teaching of Science

While the SARS story has been effective in promoting NOS understanding, there was still a lack of NOS instructional materials closely related to the school science curriculums. We also planned to produce instructional materials grounded in more local contexts and in both English and Chinese language to suit the need of local schools using either English or Chinese as the media of instruction. Thus, in September 2005, we embarked on a 2-year project, Learning and Teaching about Science Project (LaTaS), which aimed to produce local NOS curriculum resources[7] and prepare teachers for teaching NOS. We took the advice of Hodson (2006) that:

> Curriculum materials need to have a "street credibility" that can only be gained when they are developed *by* teachers *for* teachers. (p. 305)

Thus we deliberately involved teachers at the beginning stages of the design process of teaching materials. More than 50 senior secondary science teachers worked together with the university team members to develop 12 sets of teaching resources which integrate NOS knowledge with subject knowledge for the new senior secondary biology, chemistry and physics curricula (CDC 2007). Efforts were made to include as many local examples as possible on top of some classic stories of science. The topics included development of teaching materials on topics including *Disneyland in Hong Kong* to be integrated in the teaching of ecology, an abridged version of the *SARS Story* to be integrated in the teaching of infection diseases, *Nature of Light* to be integrated in the teaching of wave properties of light, *Ban of Eating Shark Fin* to be integrated with the teaching of reaction rate, etc. By specifically choosing relevant socioscientific issues or well-known classic stories of science, teachers would be more ready and willing to practise NOS teaching by making use of the materials developed by the project team in their own science classrooms. Teachers' classroom practice helped us refine the teaching materials.

Henry was among one of the teachers who helped to try out the set of instructional materials on LASIK. Like other teachers, Henry found the in-depth analysis of the lesson video of their own practice most valuable in addressing some areas for improvement. Henry noted that he had missed a number of golden opportunities in receiving student good answers on questions related the interaction of science-technology-society (STS). Unlike the usual discussion on physics questions in which teachers would guide his students to come to 'the solution', in the discussion of questions related to STS, there could be many reasonable responses. Although he was not satisfied with his implementation of the NOS activities, he was pleased to have identified the areas of improvement and was confident that he could do a much better job in his next NOS teaching. An important encouraging factor for Henry to continue NOS teaching was his realisation of students' ability and interest in learning NOS as evident in the good responses by the students (though missed by him during the trial lessons).

Henry further expressed that he found his students liked the hands-on activity that simulated the LASIK surgery[8] (Wong 2004) very much, but he found it awkward (so was his students) to have another whole lesson following the LASIK surgery to cover its related NOS and STS activities. Henry said, 'it wasn't the style of my physics teaching and my students' style of learning physics'.

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[7] Curriculum materials developed in this project are accessible at http://learningscience.edu.hku.hk/

[8] Notes to technician/teacher on the preparation of the 'cornea' and the set-up can be found in the LASIK instructional materials at http://learningscience.edu.hku.hk/

Henry's reflection told us that it was likely that the ambition in having as many NOS activities trialled and refined within the limited project period might have given teachers an impression that an NOS lesson has to be heavily loaded with NOS activities. Henry's sharing also reminded us that we should not take it for granted that teachers could naturally integrate the NOS materials with the science knowledge covered in the textbook (written before the new curriculum) in a meaningful manner. Good integration of NOS activities with the subject knowledge also requires careful planning and practice by the teacher to match with his own teaching style and his students' learning style. Just like teaching of a science topic using a textbook, each teacher could have his own style in integrating the NOS materials developed in the LaTaS project into his science classroom.

66.5.2 Modifying and Enriching Available NOS Resources

Henry, as many other participating teachers, continued to practise NOS teaching in his lessons even after the LaTaS project ended in late 2007. There are various reasons for teachers to continue their endeavour: (1) prepare students for possible questions assessing on the NOS understandings in public examination, (2) students show interest in learning NOS, (3) aware of students' ability in learning NOS and (4) positive experience in support of the 'science learning argument' by Driver and her colleagues (1996).

In Henry's further attempts in teaching NOS in 2008, he decided to address the areas of improvement identified in his trial of the LASIK materials. Firstly, instead of cramming in too many NOS ideas in one or two lessons, he infused NOS at appropriate places in a series of three double lessons each of 80 minutes during the teaching of *Nature of Light* and *Electromagnetic Wave*. Secondly, instead of bringing up each NOS idea in a fragmented way, he organised the NOS ideas in an interrelated manner. Thirdly, inspired by the experience of further learning about NOS through the SARS story, Henry included some NOS ideas which are not commonly introduced in textbooks, e.g. competition among scientists and peer review, establishment of scientific knowledge as an outcome of consensus reached by scientists and model-building as one of the typical activities of scientists in their endeavour in the pursuit of understanding of the nature. Lastly, instead of just focusing on the widely cited seven NOS aspects advocated by Lederman (1992), he went beyond the list and introduced some apparently contrasting NOS features by situating them in relevant historical contexts.

In the first double lesson, he planned to review the four wave properties, introduce Young double-slit experiment and explain the interference pattern. He tailored some NOS activities developed in the *Nature of Light* materials in the LaTaS project. He made use of the controversial arguments between Newton and Huygens about the nature of light to highlight some 'relatively negative' features about the subjectivity in science. For example, he elaborated that (i) scientists could be very 'stubborn' in holding on their beliefs due to their beloved models in explaining the natural phenomena (theory-laden observation/inference/explanation), (ii) there were two camps of scientists (one supported particle model of light and the other supported the wave model of light) and so more than one scientific models might be found coexisting in explaining a specific observation or natural phenomenon and (iii) Newton was the 'winner' as a result of submission to authority even among scientists (when both models could explain reflection and refraction of light).

In the second double lesson, he planned to review interference of light and introduce single-slit and its associated concept about diffraction. He attempted to balance the 'relatively negative' NOS features with the 'relatively positive' NOS features by highlighting the empirical evidence of Young in support of wave theory of light. He enriched the existing materials by adding the story of Poisson's challenge to Fresnel's wave theory of light. Poisson, who was a believer of particle theory of light, challenged Fresnel's arguments towards wave theory due to the lack of experimental evidence of diffraction effect of light. However, when hard experimental evidence was produced by Fresnel with the help by Arago, Poisson had to convert his belief about the nature of light based on the convincing experimental evidence.

In a subsequent double lesson, Henry then made use of the story of the discovery of DNA as one of the applications of X-ray to highlight the competitive nature of scientists and building of models through scientists' imagination and creativity. Towards the end of the series of lessons on Light Wave, he even linked all the NOS aspects covered in the topic in the form a mind map to strengthen students' appreciation of the interconnectedness of NOS features. Figure 66.2 gives a reproduction of his summary on the blackboard during the last lesson of the series on *Nature of Light* and *Electromagnetic Wave*.[9]

66.5.3 Learning from Henry's Professional Growth in Teaching NOS

Through active and persistent reflection upon each attempt of NOS teaching, Henry, as other teachers having similar commitment, has come a long way from the learning of NOS to successful design and implementation of the lessons that teaching physics as well as NOS ideas in an interconnected manner. His exemplary teaching has received recognition by different stakeholders, including science teachers who are preparing themselves to teach NOS. EDB and University colleagues have also invited him for sharing the lesson series designed by himself. To him, the greatest reward of the long journey of professional development is probably the learning of his students. It was not difficult to tell from Henry's smile when his shared students' responses received in later lessons showing their good understanding of some

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[9] Video episodes of the three series of lessons can be accessed at http://web.edu.hku.hk/knowledge/projects/science/qef_2010/d1/1b2_training_workshop.html

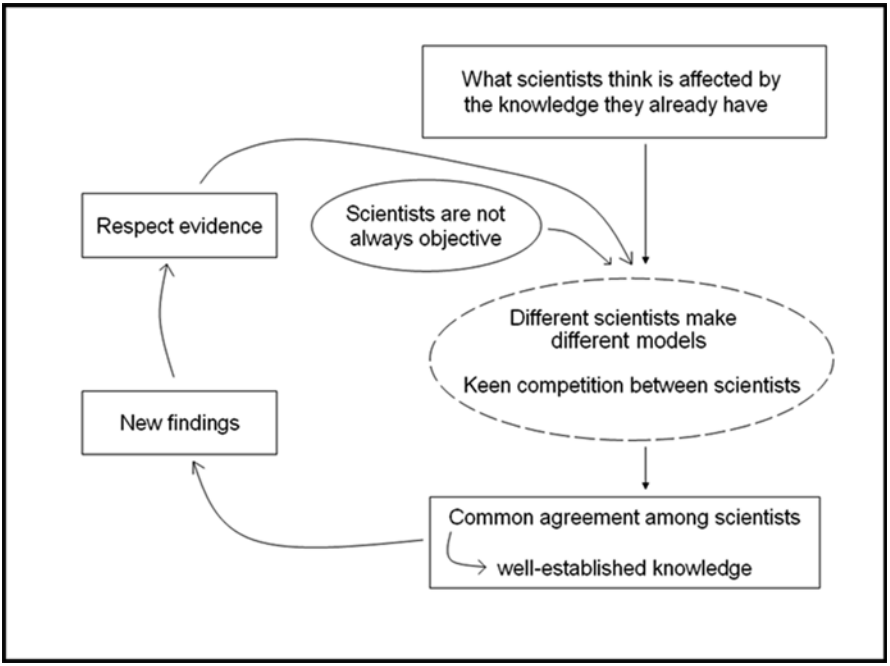

Fig. 66.2 A summary of the interconnectedness of NOS features given at the end of the lesson series

difficult NOS ideas like theory-laden observation. In his word, '*[NOS can] promote student interest in learning the content knowledge*' and '*students do learn NOS*'.

A year after the completion of the LaTaS project, EDB further supported us to conduct another 2-year project from 2008 to 2010 with a focus on the enhancement of teachers' pedagogical content knowledge (PCK) of teaching NOS. We have noted from Henry's 'revolutionary jump' in his learning curve when he attempted to plan his own lessons. Thus in the PCK project, at the outset of the project, we encouraged teachers not to simply modify and adapt the available teaching resources, but to proactively design their own instructional materials. This is indeed a goal that we wish teachers could ultimately achieve. We further explained our intention to the teachers by a Chinese proverb, (授人以魚,三餐之需;授人以漁,終生之用。). In English, it says 'Give a man a fish and you feed him for a day. Teach a man to fish and you feed him for a lifetime'.

66.6 Conclusion

In this chapter, we have compared the NOS ideas as portrayed in the curriculum standards documents, NOS ideas as portrayed in the textbooks and the teacher training for preparing teachers towards their teaching of NOS. We have also shared an exemplary lesson series conducted by a Hong Kong teacher in his classroom. Although there are variations of a few NOS aspects as portrayed in the official curriculum standards documents and school science textbooks as well as those taught in teacher training institutes, most prominent differences occur at the school classroom implementation. There are currently no reports on the implementation of NOS teaching in school science classrooms in mainland China regardless the similar degree of emphasis placed on NOS education in the official curriculum. On the other hand, the NOS teaching has taken root in Hong Kong science classrooms. The key difference mainly originates from the support and resources input from the government in realising the intended goals. We do see a related emphasis on learning science through inquiry-based approach which has taken off in science classrooms in many cities as evident in the annual national competition in mainland China since early 2000s. Schools with teachers gaining the awards will also receive funding as encouragement. In Hong Kong, the support from the government is provided to all schools through supporting institutes with experts in the area of focus and the most relevant and appropriate research and teacher professional development plans.

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Chapter 67
Trends in HPS/NOS Research in Korean Science Education

Jinwoong Song and Yong Jae Joung

67.1 Introduction

The HPS/NOS in the science education plays roles in stimulating students' motivation, in illustrating humanistic aspects of science (Jung 1994; Matthews 1994), and in helping the understanding of scientific methods (Lederman 2007; McComas and Olson 1998; Matthews 1992). In the recent days, the National Science Curriculum of Korea also highlights the promotion of students' scientific literacy which requires students' understanding of HPS and NOS (MEST 2007b; MEST 2011).

Historically, HPS and NOS have largely been of a minor attention in Korean science education. Following its liberation from Japanese occupation following the World War II, Korea's modern school education considers science as one of the core school subjects. After the Korean War (1950–1953), along the continuous national policies for industrial rebuilding and economic development, science education has continued to be the subject of national attention and public's concern. Because of this relationship with national development, science education in Korea used to focus more on practical usefulness and manpower-building-oriented approaches. In other words, school science education has often been the sources of scientific and technical majors in earlier years and of more advanced and creative scientific and engineering specialists in recent years. As a result, in Korea, HPS and NOS have largely been of a minor attention.

Science education has been a subject of systemic research activities since the establishment of Korean Association for Science Education (KASE) (formerly

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known as Korean Association for Research in Science Education: KARSE) in 1976. For the last 35 years, KASE has played the central role in researching, developing, and implementing issues of science education, mainly through its official journal, *Journal of Korean Association for Science Education* (JKASE) (formerly known as *Journal of Korean Association for Research in Science Education*: JKARSE) and biannual conferences. Beginning in 1978, JKASE was published every other year. In 1984 JKASE began publishing twice a year. Currently, eight issues (six issues in Korean and two issues in English) are published every year. As the most comprehensive and highly recognized journal, JKASE covers a whole range of areas of science education, i.e., informal as well as formal education and from preschool to tertiary levels.

Besides KASE, there are also several academic societies related to science education which target more specific groups of audience: for example, the Korean Society for Elementary Science Education (KSESE) established in 1970 and its official journal, *Journal of Korean Elementary Science Education*; the Korean Society of Biological Education (KSBE) established in 1968 and its official journal, *The Korean journal of Biology Education*; the Korean Earth Science Society (KESS) established in 1969 and its official journal, *Journal of Korean Earth Science Society*; the Korean Science Education Society for the Gifted (KSESG) established in 2008 and its *Journal of Science Education for the Gifted*; and the Korean Society for School Science (KOSSS) established in 2006 and its journal *School Science Journal*.

Similar to many countries and perhaps more strongly, science curriculum and science education research in Korea have been influenced by those in the United States. The aims of the National Science Curriculum and research trend of science education were largely similar to a decade's earlier versions of US ones. Nevertheless, the practice of school science in Korea has been inevitably dependent on social and educational conditions of the time in Korea. For example, exam-oriented, teacher-centered, and government-driven (science) education are the most prevalent conditions currently influencing Korean science education. These conditions, directly or indirectly, influence the practice and research activities of Korean science education, including HPS/NOS-related aspects. The Korean social environment that emphasizes students' hard work and high scores for entering good schools/universities makes difficult for school science education to be free from knowledge-oriented teaching and learning. And this environment would discourage for students to have ample experience to think and discuss the nature of and the historical content of science.

In this chapter, the status quo of HPS/NOS-related aspects of Korean science education are outlined, beginning with a brief summary of the history of National Science Curriculum which is the basic foundation of school science education. Next, the change of research trend of science education will be analyzed using the HPS/NOS-related papers published in JKASE for the last three decades. Finally, to find out how HPS/NOS has been incorporated in the practice of science education, HPS/NOS-related aspects in science textbooks and science teacher education will be explored.

67.2 A Brief History of National Science Curriculum of Korea

Korea has a centralized education system firmly based on its National Curriculum (Kim 2001). The National Curriculum is provided in the form of official document by the Ministry of Education, Science and Technology of Korea (MEST), and is mandatory to all schools from kindergarten to high schools. The National Curriculum of Korea has been revised regularly by the government since the first revision in 1954 (Park 2011). On average, the National Curriculum has been revised every 6–7 years (Kim 2001). At present, 2007 National Science Curriculum (MEST 2007a) is being applied to primary and middle school science education, and 2009 National Science Curriculum (MEST 2011), which is recently revised, is being applied to high school science education and will be implemented to primary and middle school after 2013.

The past curriculum reforms can be historically divided into three periods: the periods of Teaching the Syllabus (1945–1954), Course of Study (1954–1963), and Formal Curriculum (1963–present) (Kwon 2001). The period of Teaching the Syllabus was from 1945, the year of Korea's liberation from Japan, to 1954. During this period, the Korean government was the temporary government under the control by the US army. In this period, the curriculum (i.e., syllabus) was just a list of teaching items (e.g., "the existence of air," "space occupation by air," "the weight of air," "thermal expansion of air," and "compression and the use of air") without having objectives or any suggestions on teaching methods and evaluation. The syllabus of science contained not only science content but also practical arts content. Despite the inevitable influence from Japanese curriculum during the colonial rule, the school teaching during this period in large focused on the basic content and abilities of the subjects and also on overcoming the Japanese vestiges in people' spirit and everyday life.

The period of Course of Study (1954–1963) was officially named the first Korean curriculum, although there have been some debates over whether or not the Course of Study constitutes a formal curriculum. The objectives of science in this period were categorized into scientific knowledge, scientific inquiry, and attitudes toward science. The titles of content were expressed as questions (e.g., "How do the weather and seasons influence our everyday living?"). The Course of Study, however, did not include any suggestions on teaching and evaluation.

The period of Formal Curriculum can be further divided into three periods of school science curriculum: experience-centered curriculum (1963–1973), discipline-centered curriculum (1973–1981), and humanistic curriculum (1981–present). The experience-centered curriculum, that is the 2nd National Curriculum, was the first well-formalized curriculum which included objectives, content, and suggestions for teaching methods. The subjects on science were "Nature" for elementary school, "Science" for middle school, and 7 subjects (Physics I, II; Chemistry I, II; Biology I, II; and Earth Science) for high school. This curriculum was based on American progressive philosophy and emphasized everyday experience and science content.

The discipline-centered curriculum (1973–1981) was also influenced by the US science education innovation movement. The philosophy, objectives, content, and methods of teaching of the existing curriculum, i.e., the experience-centered curriculum, were changed completely. The new National Science Curriculum profoundly accepted the philosophy of discipline-centered curriculum proposed by J. S. Bruner and the Woods Hole Conference. This curriculum reorganized the content to reflect the basic concepts of science, changed the methods of instruction from rote memory to inquiry, and emphasized the teaching of science through discovery and problem-solving, students' voluntary involvement, and students' inquiry process skills. The science content of this curriculum included the five basic concepts: matter, energy, interaction, change, and life.

The humanistic curricula (1981–present) includes the 4th (1981–1987), 5th (1987–1992), 6th (1992–1997), 7th (1997–2007), 2007 Revised Curriculum, and 2009 Revised Curriculum.[1] The humanistic curricula were influenced mainly from the movements of "Science for All" and Science Technology and Society (STS). The discipline-centered curriculum had been criticized on the ground that the content was isolated from real-life situations and problems that students confront in everyday life and was too abstract and difficult for most students to understand (Kim 2001). The attention to "Science for All" and STS increased with such critiques. However, in the 4th curriculum, science content did not overcome the discipline-centered philosophy although new slogans, "Science for All" and STS, were introduced into Korean science education. The STS spirit did not explicitly appear in the objectives until the 5th curriculum. Since the 5th curriculum, "Science for All" and STS spirits were continuously strengthened until the present curriculum. One of the important changes in this period was the creation of a new combined or integrated high school science subject: "Common Science" in the 6th curriculum and "Science" in the 7th curriculum for G10, both emphasizing everyday science and decision-making. Another important change was the emphasis on scientific literacy including recognition of the relationship between STS and rational decision-making in the context of everyday life. In the 2007 and 2009 Revised Science Curricula, the terminology "scientific literacy" was expressed explicitly as the objectives of science education (MEST 2007a, 2011).

The 2007 Revised Science Curriculum, the latest curriculum applied to schools with textbooks, aims to help students understand the basic concepts of science through inquiry with interest and curiosity toward natural phenomena and objects. Students are expected to be able to develop the scientific literacy necessary for solving the problems of daily life creatively and scientifically (MEST 2009). In this curriculum, the content of "Science" includes the domains of motion and energy, materials, life, and earth and space, linking basic concepts with inquiry processes across grades and domains. In addition, these include Free Inquiry, which would provide students with the opportunities to select their own topics based on their interests, to enhance their interest in science, and to develop creativity.

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[1] After the 7th Curriculum, the revision was to be made upon its demand, thus the new Curriculum was named with the revision year instead of calling 8th or 9th.

In addition, in this Curriculum, science learning is centered around various inquiry-based activities including observing, experimenting, investigating, and discussing. Learning emphasizes independent as well as group activities for nurturing scientific attitudes and communication skills, including criticism, openness, integrity, objectivity, and cooperation. Learning also stresses the comprehensive understanding of basic concepts, rather than acquisition of fragmented knowledge, and the ability to scientifically solve problems in daily life. The core concepts of Science are taught with a close relation to learners' experiences, and students are provided with opportunities to apply science-related knowledge and inquiry skills for problem-solving in society and their daily life. By learning about science, students are to be able to recognize the relationships between science, technology, and society as well as the values of science. The particular goals of the 2007 Revised Science Curriculum are as follows:

> The Science Curriculum aims to help students understand the basic concepts of science through inquiry into natural phenomena and objects with interest and curiosity and the development of scientific thinking and creative problem solving abilities. As a result, students will be able to develop the scientific literacy necessary for solving creatively and scientifically the problems of daily life. The objectives of the Science Curriculum are to educate students so they will be able:
>
> (a) To understand the basic concepts of science and apply them to solve problems in daily life.
> (b) To develop the ability to inquire about the nature scientifically and to use this ability for solving problems in daily life.
> (c) To enhance curiosity and interest toward natural phenomena and science learning, and develop an attitude to scientifically solve problems in daily life.
> (d) To recognize the relationship between science, technology, and society. (MEST 2009, pp. 12–13)

In 2011, the 2009 Revised Science Curriculum (MEST 2011) was introduced, in which the main objective was to raise students' scientific literacy for creative and rational problem-solving. In addition, 2009 Revised Science Curriculum emphasizes the fusions among science disciplines (i.e., physics, chemistry, biology, and earth science) as well as different fields (i.e., science, technology, engineering, arts, and mathematics – often called STEAM).

Since the middle of 1980s, the description related to HPS/NOS in Science Curricula has been gradually increased. The 5th Science Curriculum, announced in, began to express the attention to NOS by declaring as its objective "… through the experience with the nature, students are expected to have interest in science and scientific literacy." The 6th Science Curriculum announced in 1992 included STS education in its objectives by saying "… students are expected to know that science influences technological developments and has close links with our everyday life." And its section for Teaching and Learning Methods stated "… to appreciate the relationship between science and life by using things available around our daily life, and to make use of what they learned during science classes in their daily life." This kind of STS-related descriptions has appeared ever since the 6th Science Curriculum. The 6th Science Curriculum also began to include HPS/NOS-related descriptions, such as "… to stimulate students' interest in and curiosity toward science through the appropriate introduction of content related to science, scientists, and current issues…." Furthermore, 2007 Science Curriculum, the curriculum focused on "scientific literacy" and creativity, presented more clearly HPS/NOS-related descriptions, such as "… to prepare the list of science books for the effective teaching of writing and discussion on the basis of materials on cutting-edge science, scientists, the history of science" (MEST 2007a, p. 25), "… to guide students to read materials on science and scientific issues, and, through the writing and discussion based on the materials, to improve their skills of scientific thinking, creative thinking, and communication" (MEST 2007a, p. 25), and "… by introducing content on cutting-edge science, scientists, current issues, to stimulate students' interest in and curiosity toward science" (MEST 2007a, p. 25).

In 2009, the National Science Curriculum (MEST 2011) emphasized scientific literacy, creative and rational problem-solving, and integrated approach, similar descriptions on HPS/NOS. For instance, the objectives included elements of scientific attitudes (such as critical ability, openness, honesty, objectivity, and cooperation) and communication skills. In particular, for G7-9 level, there is a part called "What is science?" through which students learn about science and its relevance to everyday life and develop their interest and curiosity in science. In addition, another part, "Science and Human Civilization," is included to understand scientific contributions to human civilization based on historical facts and to develop a viewpoint to see science in connections with technology, engineering, arts, and mathematics (MEST 2011, p. 66). Furthermore, its Guidance for Teaching and Learning suggests "to teach with appropriate examples the content of NOS-related issues, such as the tentativeness of science, multiplicity of science methods, feature of scientific models, the difference between observation and inference" (MEST 2011, p. 68) and recommends to introduce stories of scientists, history of science, and current scientific issues.

As illustrated so far, in general HPS/NOS-related content in Korean Science Curricula have been largely included in connection with STS approach and became recently to include a wider range of content.

67.3 HPS/NOS in Research Papers in Korea: Based on the Analysis of Papers Published in JKASE

The *Journal of the Korean Association for Science Education* (JKASE, http://www.koreascience.org/) began in 1978 and, ever since, has been the most representative science education journal in Korea, publishing the largest number of research papers on science education in Korea across the whole range of science education. In this section, the results of analysis of the trends of HPS/NOS-related papers published in JKASE for the last three decades will be reported and discussed. JKASE publishes eight times annually. Currently six of these issues are written in Korean and two issues are written in English. The papers analyzed here were from issues in both languages.

67.3.1 Types of HPS/NOS-Related Papers and Classification Method

The HPS/NOS-related papers that appeared in JKASE were classified according to its four dimensions, that is, research theme, research method, target subject, aims, and results. Referring to existing literatures which have collections of HPS/NOS-related papers (such as, *The History & Philosophy of Science in Science Teaching* (Herget 1989), *More History & Philosophy of Science in Science Teaching* (Herget 1990), *The Nature of Science in Science Education: Rationales and Strategies* (McComas 1998)), a rough category framework was developed for the classification. Based on this rough category framework, each paper was classified and then checked to see if the paper properly fit that particular category. In doing so, the framework was repeatedly revised by further dividing or combining together categories. In the process of classifying the papers, a paper could be identified with more than one category, which would provide a more comprehensive understanding of the distribution and features of the papers. As a result, eight categories in the dimension of research theme, six categories in the dimension of research method, and ten categories in the dimension of target subject for the analysis of HPS/NOS-related papers were established (Table 67.1).

When a paper was classified according to this category framework, the decision was made based on a wide consideration of not only its title or keywords but also its abstract, theme, aim, and results. Through this comprehensive process, it was found that HPS/NOS-related papers could be largely grouped into two groups: (a) researches which investigate or discuss “about” themes or theories related to HPS/NOS and (b) researches which applied ideas “based on” the results of HPS/NOS-related studies. All studies belonged to the former group, (a), were identified as HPS/NOS-related studies, whereas some belonged to the latter group were not identified as so. For example, if there is a study which investigated an effective instruction method for students’ conceptual change, it is ultimately related to HPS/NOS because instruction for conceptual change is too somehow related to philosophical arguments of science such as the nature of concept, constructivism, and knowledge development to some degree. If this kind of papers was included, in principle there would be no study which is not related to HPS/NOS. Thus, to avoid this situation, when making a judgment on papers of (b) kind, the paper was checked to see if it met the following criteria:

- Does this paper have explicit connects with HPS/NOS-related theories or concepts?
- Does this paper investigate how people think or perceive the nature of, not just simple interest in, science or scientific method or scientific concepts?
- Does this paper discuss explicitly target subject’s concept or the nature of their behaviors in terms of HPS/NOS, not just investigate their concepts or behavior?
- Does this paper make the participants or subjects to think about the nature of theories or concepts of science education and about theories or concepts related to HPS/NOS?

Table 67.1 Categories in each dimension

Dimension	Symbol	Categories
Theme	T1	Research on the trends of theories and ideas related to HPS/NOS
	T2	Research on history or historical episodes related to HPS/NOS
	T3	Research on concepts/terminologies and their nature related to HPS/NOS
	T4	Research on historical figures' life, works, and theory related to HPS/NOS
	T5	Research on social issues related to HPS/NOS
	T6	Research on curriculum and educational policies related to HPS/NOS
	T7	Research on participants' views and attitudes related to HPS/NOS
	T8	Research on instructional strategies, program, and textbooks related to HPS/NOS
Method	M1	Investigation of historical materials
	M2	Theoretical review
	M3	Quantitatively analysis on quantitative data
	M4	Quantitatively analysis on qualitative data (drawings, narrative answer, etc.)
	M5	Qualitative research
	M6	Experimental research
Participants/subject/objects	S1	Literature (published paper, historical materials, textbooks, etc.)
	S2	Kindergarten/primary students
	S3	Secondary students
	S4	University/Graduated students
	S5	In-service teachers
	S6	Experts (professor of science education, scientist, etc.)
	S7	Publics
	S8	Gifted students
	S9	Underachieve/disabled students
	S10	Facilities

– In case of studies which deal with instruction methods or programs, does this paper pay attention to their nature and change, rather than to obtaining scientific knowledge or to improving scientific skills?

67.3.2 Results of the Analysis

67.3.2.1 General Trend

Among a total of 1,362 papers published in JKASE between 1978 and 2010, the number of HPS/NOS-related papers was 246 which is 18.1 % of the total papers. Figure 67.1 shows the distribution of the HPS/NOS-related papers across the period.

As can be seen from Fig. 67.1, the number of HPS/NOS-related papers increased gradually until mid-2000s when the number started to decline slightly. However,

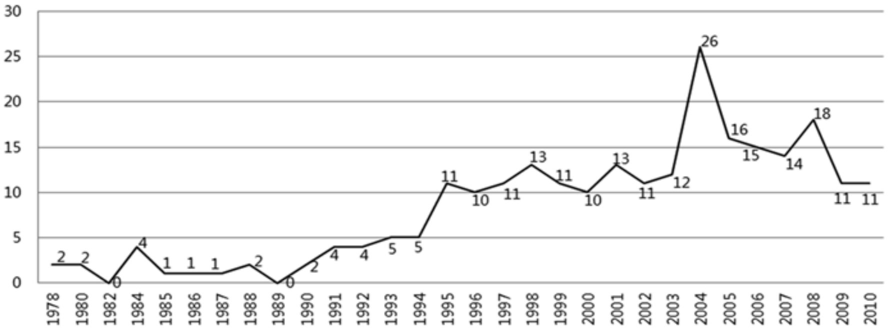

Fig. 67.1 Frequency of the papers related to HPS/NOS published in the JKASE

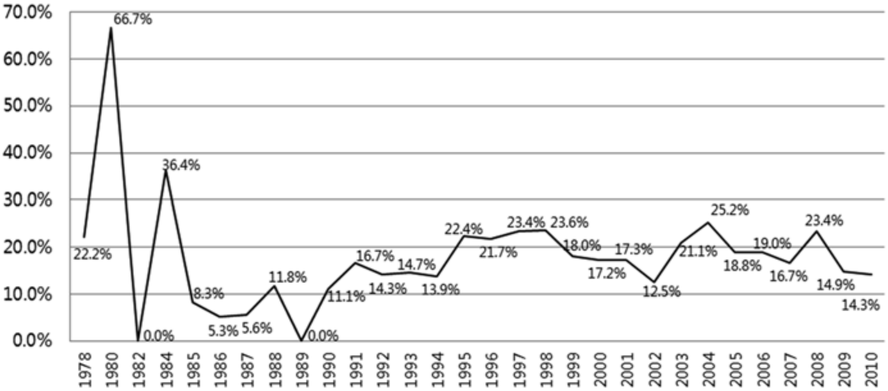

Fig. 67.2 Proportion of the papers related to HPS/NOS to the whole papers in the JKASE

since the number of total papers published by the journal itself has been increased (that is, 12 in 1978–1980, 24 in 1981–1985, 89 in 1986–1990, 171 in 1991–1995, 267 in 1996–2000, 408 in 2001–2005, 391 in 2006–2010), it is not appropriate to just compare the number of HPS/NOS papers over the periods. Figure 67.2 shows the percentage of HPS/NOS-related papers among the total papers published in JKASE in each year.

Based on Figs. 67.1 and 67.2, the proportion of HPS/NOS papers increased until the end of the 1990s, with the exception of the late 1970s and early 1980s when the total number of paper itself was very small. During this period of time when the proportion of HPS/NOS papers were increasing, Korea's 5th (1987–1992) and 6th (1992–1997) National Science Curricula were in practice. These National Science Curricula were based on the critical reflection of the previous National Science Curriculum in which too much emphasis was given to the discipline-centered approach and introduced the ideas of "Science for All" and STS in which not only scientific knowledge and process skills but also scientific attitudes and everyday scientific inquiry were emphasized at the level of the National Science Curricula (MEST, 2007a). It seems that these emphases of the National Science Curricula encouraged studies on the reconsideration of inquiry or concepts (e.g., Cho 1988; Cho 1990), on the needs and implementation methods of STS (e.g., Kwon 1991; Ha 1991; Cho 1991), and on the discussion and surveys of science-related attitude (e.g., Kwon and Park 1990; Hur 1993). In addition, following the first paper on constructivism in JKASE (Cho 1984), active research activities on the nature of science, scientific knowledge, scientific concepts, and scientific method (e.g., Cho 1988; Cho 1992) and on survey studies related to these aspects (e.g., Song and Kwon 1992; Kwon and Pak 1995) were carried out throughout the period. During the 1990s, there had been many empirical survey studies on NOS (e.g., Kwon and Park 1990; Song 1993), which made use of various newly developed instruments (such as, TOSRA, VOSTS, DAST, Nott & Wellington). The abovementioned trend during this time contributed to the growth of HPS/NOS-related papers during the 1990s.

The total number of authors of the 246 HPS/NOS-related papers in JKASE was 580, thus the average number of authors per paper was 2.4. Breaking down the period into three segments, the average author number was 1.5 during 1978–1990, 2.1 during 1981–1990, and 2.6 during 2001–2010. It is clear that the degree of co-studying for papers has been increased over time. Nevertheless, among the 580 authors of HPS/NOS-related papers, there were only 13 foreign authors, suggesting that the international collaborative research work has not been active.

Among the HPS/NOS-related papers, there were only 36 papers, i.e., 14.6 %, which were related to the history of science. Nevertheless, if we compare the numbers of history-related papers over the three decades, there was a noticeable increase: 1 paper during 1978–1990, 10 papers during 1991–2000, and 25 papers during 2001–2010.

67.3.2.2 Analysis Results of the Dimension of "Research Theme"

Table 67.2 shows the results of the analysis of the whole 246 HPS/NOS-related papers in terms of the dimension of research theme, whereas Fig. 67.3 shows the comparison of the results during the three decades.

Among the eight categories of the dimension of "research theme," the most popular one was "T7 Research on participants' views and attitudes related to HPS/NOS" with 43.9 % (i.e., a total of 108 papers). For example, like "Middle school science teachers' philosophical perspectives of science (Soh et al. 1998)" in which the authors found that the teachers predominantly held inductivistic views regardless of their major, gender, and career. Studies on students' and teachers' perceptions on the nature of science, philosophical aspects of science, STS, scientific attitudes, and science concepts occupied almost half of the HPS/NOS-related papers. Together with studies on "T8 Research on instructional strategies, program, and textbooks related to HPS/NOS" (22.8 %), this result indicates that studies on educational application and implementation of HPS/NOS were very popular. The second most popular category (27.2 %) was "T3 Research on concepts/terminologies and their nature related to HPS/NOS," suggesting that Korean science educators' attention has also been given to the

Table 67.2 Dimension of "research theme"

Symbol	Category	N	(%)	Example
T1	Research on the trends of theories and ideas related to HPS/NOS	12	4.9	Science education: constructivist perspectives (Cho and Choi 2002)
T2	Research on history or historical episodes related to HPS/NOS	14	5.7	Historical review in Foundation of London Loyal Society and France Loyal Academy (Kim 1978)
T3	Research on concepts/terminologies and their nature related to HPS/NOS	67	27.2	The role of deductive reasoning in scientific activities (Park 1998)
T4	Research on historical figures' life, works, and theory related to HPS/NOS	13	5.3	John Tyndall (1820–1894), who brought physics and the public together (Song and cho 2003)
T5	Research on social issues related to HPS/NOS	4	1.6	Brief discussion on the scientific creationism critiques (Yang 1987)
T6	Research on curriculum and educational policies related to HPS/NOS	25	10.2	An investigation into "Science-Technology-Society" curricula (Cho 1991)
T7	Research on participants' views and attitudes related to HPS/NOS	108	43.9	Middle school science teachers' philosophical perspectives of science (Soh et al. 1998)
T8	Research on instructional strategies, program, and textbooks related to HPS/NOS	56	22.8	The influence of small group discussion using the history of science upon students' understanding about the nature of science (Kang et al. 2004)
Total		299		

analysis and examination of existing theories or concepts related to HPS/NOS. For example, Park (1998) attempted to clarify the logical structure of the scientific explanation, prediction, and the process of hypothesis testing using syllogism and various concrete examples in his paper, "The role of deductive reasoning in scientific activities."

On the contrary, there were only small numbers of studies on social issues (1.6 %), on persons (5.3 %), and history or episodes (5.7 %) related to HPS/NOS. It would be quite natural that there were so many studies on the educational application or implementation of HPS/NOS in science education. However, too much emphasis on educational application could overlook the critical analysis of existing theories or perspectives and the suggestion of new theories or perspectives.

According to the comparison among the three decades (shown in Fig. 67.3), the proportions of T3 and T6 categories decreased, whereas the proportion of T8 category increased. In other words, studies on terminology/concepts/features of HPS/NOS became less popular, while those on instructional methods/programs/

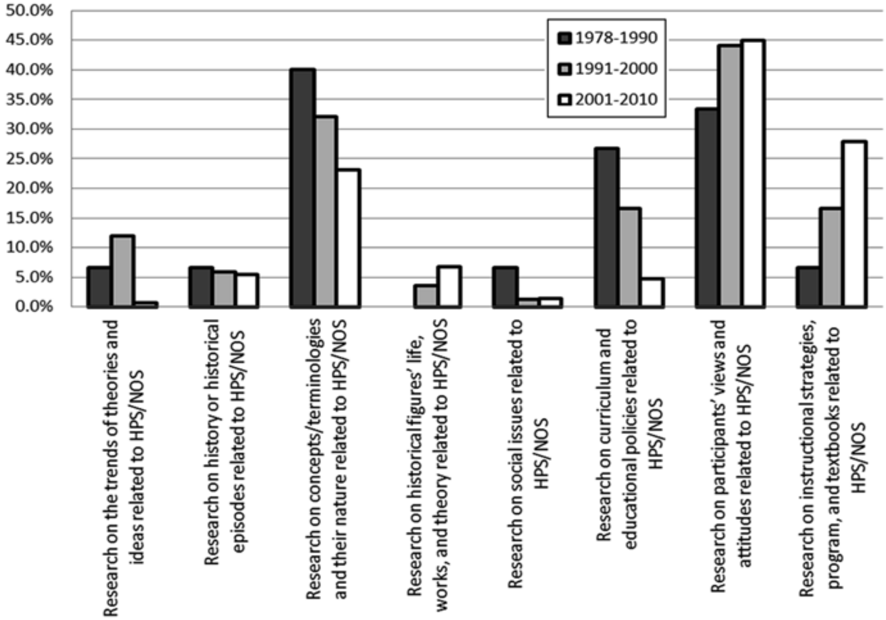

Fig. 67.3 Proportion of each "theme" to the whole HPS/NOS papers in three decades

textbooks became more popular. It seems that this trend reflects the history of Korean science education where in earlier years there were needs to carry out theoretical discussion and educational arguments for introducing HPS/NOS ideas, whereas after the 1990s there were needs to pursue more practical and concrete instructional methods and programs based on earlier more theoretical studies and on the introduction of the National Curricula emphasizing STS approaches and scientific literacy. This overall trend is also reflected in the very low proportion of "T1 Research on the trends of theories and ideas related to HPS/NOS" (only 0.7 %), like "Science education: constructivist perspectives (Cho and Choi 2002)" in which the authors described the characteristics of constructivism through reviewing the literatures from a few schools of constructivism, during the period of 2001–2010. Meanwhile, as discussed earlier, it is presumed that the continuous increase of "T7 Research on participants' views and attitudes related to HPS/NOS" was facilitated by the wide use of various newly developed instruments (such as, TOSRA, VOSTS, DAST, Nott & Wellington).

67.3.2.3 Analysis Results of the Dimension of "Research Methods"

Table 67.3 shows the result of the analysis of HPS/NOS papers in terms of research method, whereas Fig. 67.4 shows the comparison of the results during the three decades.

Table 67.3 Dimension of "research methods"

Symbol	Category	N	%	Examples
M1	Investigation of historical materials	20	8.1	The activity of an interpreter on science education during the enlightenment period in Korea: Focus on Hyun Chae (Park 2009)
M2	Theoretical review	92	37.4	A philosophical study on the generating process of declarative scientific knowledge: Focused on inductive, abductive, and deductive process (Kwon et al. 2003)
M3	Quantitative analysis on quantitative data	98	39.8	Teachers' and students' understanding of the nature of science (Han and Chung 1997)
M4	Quantitative analysis on qualitative data (drawings, narrative answer, etc.)	53	21.5	Teachers' images of scientists and their respected scientists (Song 1993)
M5	Qualitative research	18	7.3	An intensive interview study on the process of scientists' science knowledge generation (Yang et al. 2006)
M6	Experimental research	28	11.4	The effects of decision-making-centered STS (Science-Technology-Society) classes on the students' attitudes toward science and perceptions about STS (Hong 2001)
Total		309		

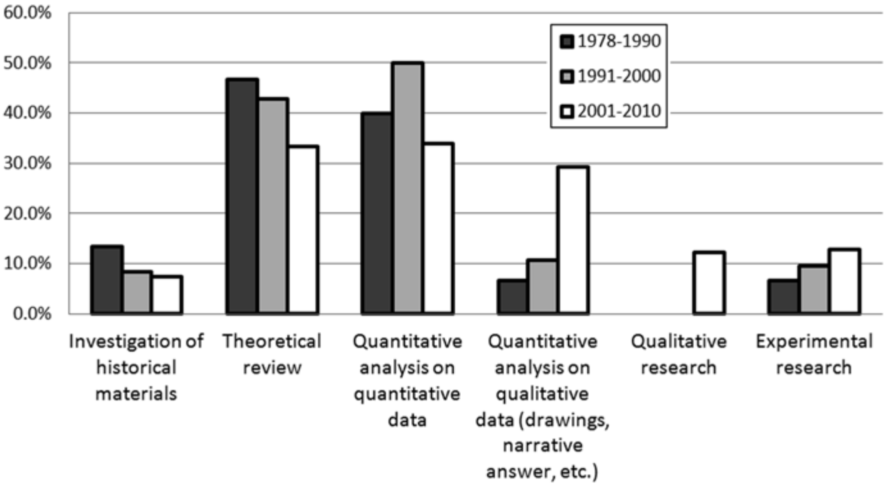

Fig. 67.4 Proportion of each "methods" to the whole HPS/NOS papers in three decades

Through the analysis of HPS/NOS-related papers in terms of research method, the most popular categories were “M3 Quantitative analysis on quantitative data” (39.8 %) and “M2 Theoretical review” (37.4 %). “M4 Quantitative analysis on qualitative data (drawings, narrative answer, etc.)” (21.5 %), exemplified by “Teachers’ images of scientists and their respected scientists (Song 1993)” in which the author explored through Draw-A-Scientist Test and analyzed the drawings with frequencies, was also relatively popular. On the contrary, “M1 Investigation of historical materials” (8.1 %) such as “The activity of an interpreter on science education during the enlightenment period in Korea: Focus on Hyun Chae (Park 2009)” and “M5 Qualitative research” (7.3 %) like “An intensive interview study on the process of scientists’ science knowledge generation (Yang et al. 2006a)” was not popular. This may illustrate that HPS/NOS-related studies in Korea during the last three decades focused more on reviews or analysis of existing relevant studies or with interpretation or investigation through the analyses of data (esp. quantitative). However, examining the trend along the timeline, a different picture of recent research methods becoming more diverse can be seen.

As shown in Fig. 67.4, recently, the two dominant methods (i.e., M2 and M3) became less popular, whereas M4 and M5 which included qualitative data and analysis became more popular especially during the 2000s. This trend of widening research methodology seems to reflect that from the 1990s Korean science education researchers began to pay attention to the weaknesses of quantitative research methods (e.g., for the investigation people’s understanding of the nature of science by Aikenhead and colleagues (1989)) and to advantages of more open and qualitative data analysis (e.g., Merriam 1988).

67.3.2.4 Analysis Results of the Dimension of “Research Subjects”

The results of the analysis of HPS/NOS-related papers in terms of the dimension of research subjects are shown in Table 67.4, whereas the comparison of the results during the three decades is shown in Table 67.5.

In terms of research subjects, the most popular categories were “S1 Literature (published paper, historical materials, textbooks, etc.)” (43.8 %) and “S3 Secondary students” (41.5 %). Conversely, the least popular categories were “S7 The general public” (1.2 %), “S9 Underachieving/Disabled students” (0.8 %), and “S10 Facilities” (0.8 %).

As shown in Fig. 67.5, as the subjects of the studies, teachers became less popular in the 2000s, whereas secondary students became much more popular from the 1990s. It is reasoned that this change was brought about by the increased research interest in students’ thinking and ideas influenced by constructivist approach from the end of the 1980s in Korea.

In case of “S8 Gifted students” like “The effects of explicit instructions on nature of science for the science-gifted (Park and Hong 2010)” in which the authors invited 20 science-gifted students as participants, there had been almost no studies until the 1990s, but then suddenly there was a sharp increase in the 2000s. This was mainly because that the Gifted Education Act was passed in 2000 and as a result,

Table 67.4 Dimension of "subjects/participants/objects"

Symbol	Category	N	%	Examples
S1	Literature (published paper, historical materials, textbooks, etc.)	108	43.8	The images of science education illustrated in the books written by modern philosophers of science (Song et al. 1997)
S2	Kindergarten/primary students	22	8.9	Perceptions about science and scientific activity of students in kindergarten and primary school (Kim and Cho 2002)
S3	Secondary students	102	41.5	Perception survey on characteristics of scientific literacy for global Science-Technology-Society for secondary school students (Ryu and Choi 2010)
S4	University/graduated students	29	11.8	Preservice science teachers' understanding of the nature of science (Nam et al. 2007)
S5	In-service teachers	29	11.8	A study on Korean science teachers' points of view on nature of science (Cho and Ju 1996)
S6	Experts (professor in science education, scientist, etc.)	8	3.3	Aims of laboratory activities in school science: A Delphi study of expert community (Yang et al. 2006)
S7	The general public	3	1.2	Science-related attitudes of Korean housewives (Kim et al. 2004)
S8	Gifted students	12	4.9	The effects of explicit instructions on nature of science for the science-gifted (Park and Hong 2010)
S9	Underachieving/disabled students	2	0.8	A investigation of the attitudes toward science and scientific attitude for the underachievers (Yi and Kim 1984)
S10	Facilities	2	0.8	Developing active role of science museum in educating on ethical issues on science and technology: Four case studies (Choi 2004)
Total		317		

government administrative and financial supports were put in place, such as establishing Gifted Education Institutions in universities and local education offices. This might show that studies related to HPS/NOS can also be influenced by national policies and governmental supports.

In sum, the analysis of HPS/NOS-related papers published in JKASE (*Journal of Korean Association for Science Education*) from 1978 to 2010 shows that HPS/NOS-related studies have been continuously carried out largely on HPS/NOS-related people's ideas/views/attitudes, on instructional methods or programs, and on terms/concepts/features of HPS/NOS. In general, although there has been some concentration on specific areas in terms of research method, research subjects, and purpose and results, recently research with diverse purposes and methods became more and more popular.

Table 67.5 Analysis of the type and organization of the historical information

	Textbooks								
Subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
1.1. Scientists									
1.1.1. Scientists' life									
1.1.1.1. Biographic data	–	–	2	7	6	15.5	8	43.0	81.5
1.1.1.2. Personal characteristics	–	–	–	–	–	–	–	0.5	0.5
1.1.1.3. Episodes/anecdotes	1	–	1	5	0.5	1.5	1	0.5	10.5
1.1.2. Scientists' characteristics									
1.1.2.1. Famous/genius	2	1	2	7	1	–	2	0.5	15.5
1.1.2.2. Ordinary	–	–	–	–	–	–	–	–	–
1.2. Evolution of science									
1.2.1. Type of evolution									
1.2.1.1. Mention to a science discovery	1	1	–	2	6	8	5	32	55
1.2.1.2. Description of a science discovery	3	3	1	6	2	1.5	2	3.5	22
1.2.1.3. Mention to discreet periods					0.5	1	0.5	4.5	6.5
1.2.1.4. Linear and straightforward	4	–	4	1	1.5	11	1.5	12	35
1.2.1.5. Real evolution	–	–	3	1	–	–	–	0.5	4.5
1.2.2. Responsible people									
1.2.2.1. Individual scientists	2	1	5	10	8.5	16.5	8	39.5	90.5
1.2.2.2. Group of scientists	1	1	2	–	1	2.5	1	10.5	19
1.2.2.3. Scientific community	2	–	3	–	1.5	5	0.5	2.5	14.5

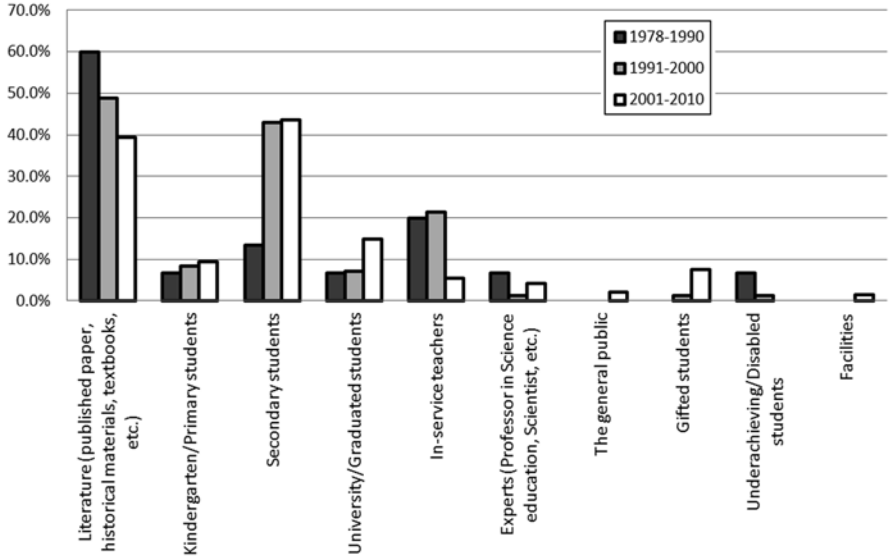

Fig. 67.5 Proportion of each "subjects/participants/objects" to the whole HPS/NOS papers in three decades

67.4 HPS/NOS in Textbooks in Korea

The science textbook is the most basic instructional material used in schools, particularly countries like Korea where school education is considerably centralized. Thus, the analysis of the content related to HPS/NOS in science textbooks would provide a good indication showing how much of HPS/NOS-related content are taught in schools. Existing studies on HPS/NOS content in textbooks (e.g., Cho 2008; Lee and Shin 2010; Leite 2002; Niaz 2000) also provide some meaningful references to this analysis. In this section, the analysis is done with the most recent science textbooks in Korea, which were published between 2009 and 2011 according to 2007 National Science Curriculum. It is expected that the results of the analysis illustrate the current practice of HPS/NOS-related instruction in Korean school science education.

67.4.1 The Method of Analysis

67.4.1.1 Textbooks Analyzed

This analysis was done with textbooks for G3 to G10 Science subject in Korea. The textbooks were written based on 2007 National Science Curriculum, except for G10 of which National Science Curriculum was revised once again in 2009. For G3 to G6 which are parts of elementary school years, there is only one kind of Science textbooks because there is a system of national textbooks for elementary schools in Korea (see textbooks of G3-1–G6-2 in the References). For G7 to G10 for which different kinds of Science textbooks are available through the government approval, the most two popular Science textbooks for each grade were chosen and analyzed (see textbooks G7-A–G10-B in the References).

67.4.1.2 Analysis Framework and Method

The content related to the history of science was analyzed based on the framework of Leite (2002). However, since in Korea there are no official student workbooks provided for G7 to G10 students and no separate lists of content according to learners' levels in science textbooks, it was not easy to use directly the analysis framework of Leite (2002). Thus, the frameworks of Choi, Yeo, and Woo (2005) and of Lee and Shin (2010) were consulted, which modified Leite's framework for better adjustment to Korean situation, and added some new items which were turned out to be necessary through the actual analysis. Tables 67.5, 67.6, 67.7, and 67.8 in the Sect. 67.4.2 show the framework for analyzing historical content of Korean science textbooks used in this study and the results.

There were four dimensions for analyzing historical content of the science textbooks: "Type and organization of the historical information" (see Table 67.5 in the

Table 67.6 Analysis of the content of the history of science

	Textbooks								
Subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
2.1. Contexts to which historical information is related									
2.1.1. Scientific	2	3	8	7	3.5	12	3.5	13	52
2.1.2. Technological	7	3	4	4	1.5	4	–	6	29.5
2.1.3. Social	1	–	2	1	0.5	1.5	0.5	2	8.5
2.1.4. Political	–	–	–	–	–	0.5	–	–	0.5
2.1.5. Religious	–	–	–	–	–	–	–	–	–
2.2. Domain of science content									
2.2.1. Physics	4	1	2	5	1	1.5	3	13.5	31
2.2.2. Chemistry	2	1	2	3	3.5	7	2	5.5	26
2.2.3. Biology	1	1	–	–	1	1	1	17.5	22.5
2.2.4. Earth science	1	1	4	2	7	12.5	3	16	46.5
2.3. Domain related to the purpose of science education									
2.3.1. Cognitive domain	2	3	6	7	9.5	17.5	8	34	87
2.3.2. Affective domain	–	–	2	2	–	–	–	–	4
2.3.3. Process skill domain	–	–	3	1	–	2	0.5	–	6.5
2.3.4. STS	8	3	4	4	2.5	2.5	0.5	17.5	42

Sect. 67.4.2), “Content of history of science” (see Table 67.6 in the Sect. 67.4.2), “Source of history of science” (see Table 67.7 in the Sect. 67.4.2), and “Role of the historical content in science teaching and learning” (see Table 67.8 in the Sect. 67.4.2). The dimension of “Type and organization of the historical information” is to see what kinds of and how the historical information is treated in science textbooks and is consisted of two subdimensions: “Scientists” and “Evolution of science.” “Scientists” subdimension is divided further into two, “scientists’ life” and “scientists’ characteristics,” each of which is further divided into two or three items. The dimension of “Content of history of science” is to see the features of historical content in science textbooks and is consisted of three subdimensions – “Context to which historical information is related,” “Domain of science content,” and “Domain related to the purpose of science education” – each of which is divided further into several sub-subdimensions. The dimension of “Source of history of science” is to see the features of the sources of historical information and materials and is consisted of three subdimensions – “Materials used to present the historical information,” “Culture/Nations related to history of science,” and “Times related to history of science” – each of which is divided further into several sub-subdimensions. Lastly, the dimension of “Role of the historical content in science teaching and learning” is to see the actual roles of the historical content shown in textbooks in terms of science teaching and learning and is consisted of two subdimensions – “Fundamental” and “Complementary – each of which is divided further into several sub-subdimensions.

On the other hand, the content related to the philosophy of science or NOS was analyzed based on the framework of Choi, Choi, and Jin (2010). This framework is based on that of Leite (2002) but with a revision after considering VOSTS items in

Table 67.7 Analysis of the source of the history of science

	Textbooks								
Subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
3.1. Materials used to present the historical information									
3.1.1. Scientists' pictures	1	–	5	8	3	2.5	2	11.5	33
3.1.2. Pictures from machines, laboratory equipment, etc.	3	1	2	2	1	−1	–	1	11
3.1.3. Original documents/texts	–	–	–	–	–	1.5	–	0.5	2
3.1.4. Historical experiments	–	–	3	3	0.5	–	1.5	0.5	7.5
3.1.5. Secondary sources	–	–	–	–	–	1	–	–	1
3.1.6. Texts by the textbook author(s)	5	2	8	9	2	5	0.5	3	34.5
3.1.7. Pictures of science cultural heritage	1	1	2	2	1	0.5	0.5	0.5	8.5
3.1.8. Pictures of historical event	–	1	1	–	1.5	4.5	0.5	2.5	11
3.2. Culture/nations related to history of science									
3.2.1. The Eastern culture/nations									
3.2.1.1. Korea	1	1	1	3	3	2.5	0.5	2	14
3.2.1.2. China	–	–	–	–	–	–	–	0.5	0.5
3.2.1.3. Japan	–	–	–	–	–	–	–	–	–
3.2.1.4. General Orient	–	–	–	–	–	0.5	–	–	0.5
3.2.1.5. Other Eastern culture/nations		–	–	–	0.5	1	0.5	–	2
3.2.1.6. Not mention to particular Culture/nation		–	–	–	–	–	–	–	–
3.2.2. The Western culture/nations									
3.2.2.1. United Kingdom	1	1	–	–	3.5	3.5	1.5	9	19.5
3.2.2.2. France	–	–	1	–	0.5	2	1.5	3	8
3.2.2.3. Germany	–	–	–	–	3.5	1.5	1.5	7	13.5
3.2.2.4. Italy/Greece	–	–	2	2	–	4	2.5	2	12.5
3.2.2.5. USA/Canada	1	2	–	1	0.5	1	1.5	9	16
3.2.2.6. General West	–	–	–	–	–	–	–	0.5	0.5
3.2.1.7. Other Western culture/nations	1	–	1	–	2	2.5	1.5	9	17
3.2.1.8. Not mention to particular Culture/nation	1	–	3	4	1	11	3	17.5	40.5
3.2.3. Others									
3.2.3.1. Other culture/nations	–	–	–	–	0.5	2	0.5	0.5	3.5
3.2.3.2. Not mention to particular Culture/nation	4	–	–	–	–	–	–	4.5	8.5
3.3. Times related to history of science									
3.3.1. Before around 14C	2	1	–	–	1.5	6.5	2	2.5	15.5
3.3.2. Around 14C–16C	2	–	–	2	1.5	4	1	2.5	13
3.3.3. Modern times (17–19C)	3	2	1	6	3.5	10.5	4.5	22.5	53
3.3.4. Contemporary times (20C-)	6	2	1	3	6	6.5	2.5	29	56
3.3.5. Not mention to particular times	–	–	–	–	1	4	0	4	9

Aikenhead, Ryan, and Fleming (1989); national standards of several countries analyzed by McComas and Olson (1998); and VNOS items in Lederman, Abd-El-Khalick, Randy, and Renée (2002). Items of "Scientists' life" and "Scientists' attribute"

Table 67.8 Analysis of the role of historical content in science teaching and learning

	Textbooks								
Subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
4.1. Fundamental	–	–	5	3	4.5	17.5	3.5	37	70.5
4.2. Complementary	8	4	3	7	8	6.5	5.5	15.5	57.5

Table 67.9 Analysis of the responsibility and role of scientists, the development of scientific knowledge, and scientific methods

	Textbooks								
Dimensions and subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
1. Responsibility and role of scientists									
1.1. Personal level	2	1	4	5	2	6.5	1	8	29.5
1.2. Social level	6	4	6	5	0.5	–	–	0.5	22
2. Development of scientific knowledge									
2.1. Model of development									
2.1.1. Cumulative model	1	–	2	3	2	4	0.5	3	15.5
2.1.2. Evolutionary model	–	–	1	1	0.5	2	–	3.5	8
2.1.3. Revolutionary model	–	–	–	–	–	0.5	–	2.5	3
2.1.4. Gradual model	–	–	1	–	1	2	0.5	3.5	8
2.2. Introduction scope of "development of science"									
2.2.1. Introduction of scientific developments only	1	–	–	–	1	4	–	2	8
2.2.2. Introduction of scientific developments with the background and consequences of them	–	–	4	4	2	4.5	1	10.5	26
3. Scientific methods									
3.1. Inductive method	7	3	3	2	2	6	2	5.5	30.5
3.2. Deductive method (including the method of testing hypothesis)	1	3	6	7	2.5	4.5	2	7.5	34
3.3. Abductive method (included in generating hypothesis)	1	3	5	5	1	1.5	0.5	4	21
3.4. Social consultation method	–	–	1	–	–	–	–	0.5	1.5

in the framework of Choi, Choi, and Jin (2010), which earlier appeared in the framework for the content related to the historical content of science, were excluded. In addition, through the analysis of textbooks, it was found that there was a need to introduce a few new classifications and to make a slight revision of the framework. Tables 67.9 and 67.10 in the Sect. 67.4.3 show the framework used in this study to analyze textbook content related to the philosophy of science or NOS and the results.

The framework of analyzing philosophical/NOS content in science textbooks is consisted of 6 dimensions: "Responsibility and role of scientists" (see Table 67.9 in the Sect. 67.4.3), "Development of scientific knowledge" (see Table 67.9 in the Sect. 67.4.3), "Scientific methods" (see Table 67.9 in the Sect. 67.4.3), "Science-Technology-Society relation" (see Table 67.10 in the Sect. 67.4.3), "Domain related

Table 67.10 Analysis of the Science-Technology-Society relation, domain related to the purpose of science education, and role of the NOS content in science teaching and learning

	Textbooks								
Dimensions and subdimensions	G3	G4	G5	G6	G7	G8	G9	G10	Total
4. Science-Technology-Society relation									
4.1. Science-Technology relation									
4.1.1. Positive relation	–	2	3	2	1.5	1	–	1	10.5
4.1.2. Negative relation	–	–	–	–	–	–	–	–	–
4.2. Science-Society relation									
4.2.1. Positive relation	2	1	3	–	–	–	0.5	0.5	7
4.2.2. Negative relation	–	–	–	–	–	–	–	–	–
4.3. Science-Technology-Society relation									
4.3.1. Positive relation	6	4	–	4	0.5	–	0.5	0.5	15.5
4.3.2. Negative relation	–	1	–	–	0.5	–	–	–	1.5
5. Domain related to the purpose of science education									
5.1. Cognitive domain	2	2	5	5	3.5	8.5	0.5	12.5	39
5.2. Affective domain	1	–	2	1	1	–	–	0.5	5.5
5.3. Process skill domain	7	5	9	6	1.5	1	1	–	30.5
5.4. STS	6	6	5	6	0.5	–	0.5	0.5	24.5
6. Role of the NOS content in science teaching and learning									
6.1. Fundamental	–	1	6	7	1.5	6.5	–	10.5	18.5
6.2. Complementary	12	11	6	7	3.5	3	2	3	47.5

to the purpose of science education" (see Table 67.10 in the Sect. 67.4.3), and "Role of the historical content in science teaching and learning" (see Table 67.10 in the Sect. 67.4.3). The dimension of "Responsibility and role of scientists" is to check the viewpoints of the textbooks describing scientists' roles and is consisted of two subdimensions: "Personal level" and "Social level." The dimension of "Development of scientific knowledge" is to check on what basis of the model textbooks describe the development of scientific knowledge and is consisted of two subdimensions: "Model of development" and "Introduction scope of 'development of science.'" The dimension of "Scientific methods" is to check the viewpoints of textbooks toward scientific methods and is consisted of four subdimensions: "Inductive method," "Deductive method (including the method of testing hypothesis)," "Abductive method (included in generating hypothesis)," and "Social consultation method." The dimension of "Science-Technology-Society relation" is to check whether textbooks describe the positive or negative relations among science, technology, and society and is consisted of three subdimensions: "Science-Technology relations," "Science-Society relation," and "Science-Technology-Society relation." The dimensions of "Domain related to the purpose of science education" and of "Role of the historical content in science teaching and learning" are consisted of the same subdimensions as earlier in the framework used for the analysis of historical content of textbooks.

For the analysis, the frequencies of items or sub-subdimensions were checked. If a part of a textbook dealt with one discovery or event or theme (either of the history of science or of the philosophy of science or NOS), it was counted as one occasion, regardless of the number of pages. In other words, two separate historical contents can be identified from a single page or more than one page can be regarded as dealing with a single historical content. On the contrary, in case of having two or more sub or sub-subdimensions or items in a single content related either to the history of science or to the philosophy of science/NOS, the frequency was counted as many as needed. The frequency was counted as a year total. That is, in the case of science textbooks for G3–G6 where there is only one kind of government-approved textbook, the frequency was calculated as a sum for two semesters. In the case of science textbooks for G7–G10 where the most popular two textbooks were analyzed, the frequency was calculated as an average of the sums of the two textbooks for two semesters.

67.4.2 Results of the Analysis of the Historical Content of Science Textbooks

Table 67.5 shows the results of the analysis of the type and organization of the historical content of Korean science textbooks for G3–G10.

As shown in Table 67.5, in the case of “scientists’ life,” the historical content of scientists’ life was mostly on biographical data (such as their names, years of birth, or death) which appeared with 81.5 cases, while the content on the episodes/anecdotes or personal characteristics of scientists was relatively very few appearing with 10.5 cases and 0.5 cases, respectively. This result is in accordance with the results of previous studies on Portuguese textbooks by Leite (2002) and on Korean textbooks based on the previous National Science Curricula by Choi and colleagues (2005) and by Lee and Shin (2010). This result shows that the descriptions of scientists tend to provide fragmented information, rather than meaningful narrative elements, of the scientists. Nevertheless, the appearance (i.e., 10.5 cases) of the episodes/anecdotes is in fact much higher than the result of the study by Lee and Shin (2010) which showed only 0.7 cases with the textbooks (for G3–G7) based on the 7th National Science Curriculum (MOE 1997). In fact, the elementary science textbooks (for G3–G6) based on the 7th National Science Curriculum had no appearance of episodes/anecdotes. The big increase of the episodes/anecdotes in the elementary science textbooks based on 2007 National Science Curriculum was made by introducing new sections, called “Science Stories” and “Inquiry by Scientists,” to the elementary science. These sections encouraged to have ample and diverse descriptions on scientists.

In the case of “scientists’ characteristics,” scientists were described in 15.5 cases as being of different characteristics – such as with full of curiosity and endless efforts to achieve exactness or with talented ideas – from ordinary people, while there was no description of scientists as ordinary people. For example, the process of which A. L. Wegener claimed the theory of continental drift and was searching for the grounds of his claim in a very rigorous way (G6-1, pp. 188–191) and the story of which Dr. Jangchun Woo (a famous pioneering Korean scientist) saved the people from the shortage of food through his talented ideas and enormous passion (e.g., G10-A, p. 294) are some examples of scientists as persons with exceptional abilities and attitudes. This kind of the description of scientists as exceptional abilities should be reconsidered, especially if we wish to encourage people's science-friendly attitudes and students' careen guidance toward science and engineering.

For "type of evolution" in "Evolution of science," the most common items described were "mention to a science discovery" (55 cases), "linear and straightforward" (35 cases), and "description of a science discovery" (22 cases), while "real evolution" and "mention to discreet periods" were only 4.5 cases and 6.5 cases, respectively. However, compared with that (i.e., 1.3 cases shown in Lee and Shin (2010)) of the science textbooks based on the 7th National Science Curriculum, "real evolution" became more popular, and this was also due to the introduction of "Science Stories" and "Inquiry by Scientists" sections. For example, the science textbook for the 2nd semester of G6 describes the whole process of the discovery of oxygen across its four pages, which includes A. L. Lavoisier's criticism to and experiment against J. Priestley's claim, discovery of the nature of air as the mixture of various gases, and the naming process of oxygen (G6-2, pp. 162–165).

In the case of "responsible people," the description of "individual scientists" (90.5 cases) was much more popular than those of "group of scientists" (19 cases) and of "scientific community" (14.5 cases), implying that historical content in the textbooks was largely focusing on the achievements of individual scientists.

Table 67.6 shows the analysis results of the content of the history of science. Popular contexts to which historical information is related were "scientific context" (52 cases), "technological context" (29.5 cases), and "social context" (8.5 cases), while "political context" and "religious context" were rarely or no described. The only "political context" was the case of the development of the Western calendar in which the role of the rulers is described as an important factor (G8-A, p. 351). Thus, in terms of the contexts, it can be argued that the textbooks still have rather narrow descriptions of the history of science, exclusively focusing on its scientific and technological contexts.

The analysis in terms of "Domain of science content" shows that the historical content was from "earth science" (46.5 cases), physics (31 cases), chemistry (26 cases), and biology (22.5 cases). Despite a higher ratio from "earth science," the distribution across the domains of science seems not to be overly biased. One thing to pay attention is that the vast majority of "biology" domain was from G10, 17.5 out of 22.5.

In the case of "Domain related to the purpose of science education," "cognitive domain" and "STS" were found to be most common, 87 cases and 42 cases, respectively, while "affective domain" and "process skill domain" were less common, 4 cases and 6.5 cases, respectively. This result with current science textbooks is rather similar to that of the result with previous science textbooks based on the 7th National Science Curriculum (Lee and Shin 2010) (that is, cognitive domain 96.7 cases, STS

16.9 cases, process skill domain 5.3 cases, and affective domain 1 case), except for the fact that "STS" became more popular. This result shows that although historical content can be effective in stimulating students' motivation, in illustrating humanistic aspects of science (e.g., Jung 1994; Matthews 1994) and in helping the understanding of scientific methods (e.g., Matthews 1992), the treatment of historical content in science textbooks is still biased toward its "cognitive" and "STS" aspects.

Table 67.7 shows the results of the analysis of "Source of History of Science" in terms of its materials form, cultural/national background, and historical period. The most popular forms of historical information were "texts by the textbook author(s)" (34.5 cases) and "scientists' pictures" (33 cases), such as M. Faraday, G. Galilei, and R. J. E. Clausius. On the contrary, original documents/texts were little used, as is seen in only 2 cases (e.g., the chemistry textbook and a part of element table by A. L. Lavoisier – G8-A, p.54). Despite the difficulty of the translation into Korean, for the credibility of historical information, it would be better to have more original documents/texts in science textbooks. On the other hand, in the case of photos and pictures of scientists, while there was no case in the elementary science textbooks (for G3–G6) based on the 7th Science Curriculum (Lee and Shin 2010), there were 14 cases in those based on 2007 National Science Curriculum, such as C. Alessandro Volta (G5-1, p. 86), L. Pasteur (G5-1, p. 166), and M. Faraday (G6-1, p. 182).

The "culture/nation" which had been the background of the history of science turned out to be overwhelmingly Western (in total 127.5 cases) compared with those from Eastern cultures (in total 17 cases). Furthermore, among those from Eastern cultures, 14 cases were Korean while the rest (3 cases) were from the rest of the Eastern region. This distribution, heavily biased toward the Western, would reflect the situation that most of school science content is in fact rooted into the Western science. It seems that this result is somehow related to the heavy emphasis on "cognitive domain" over "affective domain" in "Domain related to the purpose of science education" (see Table 67.7). That is to say, since the purpose of introducing of the history of science was mainly to help students' understanding of scientific concepts, it might have been natural to focus on the Western history which would be more directly linked with scientific concepts, rather than the Eastern history which would be more useful in terms of affective domains.

The analysis of "Times related to the history of science" shows that those of "contemporary times (20C-)" (56 cases) (e.g., stories of Apollo 8 & 11 (G8-A, p. 320), the development of solar cells (G10-A, p. 424)) and "modern times (17C–19C)" (53 cases) (e.g., Boyle's discovery of indicator (G6-1, pp. 62–63), and Lavoisier's naming of oxygen (G6-2, pp. 162–156)) were the most popular sources of the history of science. The high appearance of "modern times" is easily understood when it is noticed that the majority of school science content are on the historical developments of that particular period of the history. The appearance of "contemporary times" is in fact higher than that (38.4 cases (Lee and Shin 2010)) of the 7th National Science Curriculum, and this seems to be the result of 2007 National Science Curriculum's emphasis on scientific literacy (MEST 2007a, 2009).

Table 67.8 shows the result of the analysis of the role of historical content. The role of textbooks historical content in science teaching and learning was found to be slightly more frequently used as “Fundamental” than as “Complementary,” although the trend was reversed at the elementary school level especially for G3–G4.

As indicated in Tables 67.5, 67.6, 67.7, and 67.8, for the most part, science textbooks for G10 appear to have much more historical content than those for other grades. This is because science textbooks for G10 were developed on the basis of the most recent curriculum, 2009 National Science Curriculum, which emphasizes the improvement of students’ scientific literacy through various materials for the teaching of meanings, values, and roles of science instead of fragmented knowledge of each discipline of science.

67.4.3 Results of the Analysis of the Philosophy of Science/NOS-Related Content

The analysis of the philosophy of science/NOS content of Korean science textbooks for G3–G10 resulted in a variety of dimensions and subdimensions. The results of the analysis for “Responsibility and role of scientists,” “Development of scientific knowledge,” and “Scientific methods” are shown in Table 67.9.

For the “Responsibility and role of scientists,” the “personal level” (29.5 cases) was found to be more popular than the “social level” (22 cases). However, at the elementary level, the trend was reversed. In elementary science textbooks, 21 cases of the “social level” were presented while 12 cases of the “personal level.” For example, there was a great deal of content on the social roles and responsibility of scientists, such as, the story of Jane Goodall’s study of chimpanzees. Jane Goodall’s study was described in details in conjunction with the activities of environmental and animal protection groups (G3-2, pp. 66–67). Another example was a description of the beneficial contributions of scientists to the development of artificial internal organs based on their knowledge on human body (G5-2, p. 54). Once again, this increase illustrates the effect of introducing the sections for “Science Stories” and “Inquiry by Scientists” in 2007 National Science Curriculum.

In the case of “Mode of development” of the “Development of scientific knowledge,” the “cumulative model” (15.5. cases) was found to be most common, followed by “evolutionary model” (8 cases), “gradual model” (8 cases), and “revolutionary model” (3 cases). This bias toward the “cumulative model” of scientific knowledge development can be an obstacle in introducing the diverse and complicate nature of scientific knowledge. Nevertheless, considering the result of the previous study by Choi and colleagues (2010) with science textbooks based on the previous 7th National Science Curriculum showing that “cumulative model” was 89.1 % and that there was no description on the model of scientific knowledge development in elementary science textbooks, it is a remarkable improvement. In addition, the current science textbooks include many more cases of “introduction of scientific developments with the background and consequences of them” (26 cases) than those of “introduction of scientific developments only” (8 cases).

In the case of "Scientific methods," "Deductive method (including the method of testing hypothesis)" (34 cases) and "Inductive method" (30.5 cases) were found to be much more popular than "Social consultation method" (1.5 cases). The extremely low description of "Social consultation method" illustrates well how current science textbooks overwhelmingly adapt traditional models of scientific development. Nevertheless, considering the result of Choi and colleagues (2010) in which, with no classification of "Abductive method (included in generating hypothesis)," "Inductive method" (84.5 %) was the vast majority compared with "Deductive method (including the method of testing hypothesis)" (15.5 %) and "Social consultation method" (no case), it can be said that the current science textbooks adapt more diverse views of scientific development. This tendency can also be found in the fact that there were 21 cases of the descriptions on "Abductive method (included in generating hypothesis)." In the case of "Abductive method (included in generating hypothesis)," the cases in which the process of abductive inference (Peirce 1878) based on similarity were mentioned or in which students were guided to have tentative explanations after observation activities were counted.

Meanwhile, in contrast to the situation that there had been no description on scientific method in the previous elementary science textbooks based on the 7th National Science Curriculum (Choi et al. 2010), the current elementary science textbooks contain 47 cases of descriptions on scientific method. It is presumed to be caused by the 2007 National Science Curriculum's introduction of "Free Inquiry" in which students are expected to carry out their own long-term investigations and thus to have experience of choosing inquiry topics, selecting inquiry methods, transforming inquiry data, and reporting inquiry results (MEST 2007a). Together with "Science Stories" and "Inquiry by Scientists," the introduction of "Free Inquiry" encourages the description of scientific methods.

Table 67.10 shows the result of the analysis of "Science-Technology-Society relation," "Domain related to the purpose of science education," and "Role of the NOS content in science teaching and learning."

For "Science-Technology-Society relation," there were 10.5 cases of "Science-Technology relation," 7 cases of "Science-Society relation," and 17 cases of "Science-Technology-Society relation." Among them, while the cases of the first two were only positive ones, 1.5 cases out of the 17 cases of the third were negative ones, such as "… the development of industry and the growth of population demand more fresh water. However, due to the environmental destruction and water pollution, the amount of usable water decreases and thus we are making a great deal of efforts to secure the water resource. We need water conservation" (G4-1, p. 125).

For "Domain related to the purpose of science education" which was further classified according to the major purpose areas stated in the 2007 National Science Curriculum, 39 cases of "cognitive domain," 30.5 cases of "process skill domain," 24.5 case of "STS," and 5.5 cases of "affective domain" were identified. Compared with that with historical content (6.5 cases), the number of cases of "process skill domain" with philosophical content/NOS here, i.e., 30.5 cases, is much higher. This is thought to be caused by the introduction of "Free Inquiry" activities in the 2007 National Science Curriculum (MEST 2007a).

For “Role of the NOS content in science teaching and learning,” there were 47.5 cases of “Complementary” which is much higher than that of “Fundamental.” This tendency was more apparent with lower grades, implying that philosophical content/NOS descriptions are treated of more importance with higher grade students.

In sum, in Korean science textbooks for G3 to G10, the historical and philosophical/NOS content is still represented with a bias in areas like the descriptions on scientists, the evolution of science, the sources of historical materials, the developmental model of scientific knowledge, scientific methods, and the roles in science teaching learning. Nevertheless, as the new 2007 (or 2009) National Science Curriculum introduced new sections like “Science Stories,” “Inquiry by Scientists,” and “Free Inquiry,” new science textbooks emphasized scientific literacy and inquiry activities and thus included more frequent and diverse descriptions of the history of science and the philosophy of science/NOS-related aspects.

67.5 HPS/NOS in Teacher Education Programs in Korea

The practice of education is heavily depending on teachers’ actions. Thus the professional development of teachers must be one of the most important elements of improving the quality of education. The teachers’ professionalism includes the speciality in teaching methods (Shulman 1987) and the specific abilities required in school practice (Castetter 1986). The professional development of teachers is considered as the starting point of a systemic innovation of education (Desimone et al. 2002; Seo et. al. 2010; Smith and O’day 1991), and the quality of science education depends on the professionalism of teachers who teach science. The professional development of teachers needs to be considered at the two different levels, preservice and in-service levels. In this respect, HPS/NOS-related practice of teaching science can also be examined with preservice as well as in-service teacher programs. Thus, this section will analyze the programs related to HPS/NOS for preservice and for in-service teacher education programs and investigate the efforts to improve the HPS/NOS-related teachers’ professionalism.

67.5.1 The Method of Analysis

67.5.1.1 Programs Analyzed

The analysis of the ratio of HPS/NOS-related preservice programs was done with the curricula of national universities. In Korea there are ten National Universities which provide preservice teacher education programs for secondary science and ten National Universities of Education which provide preservice teacher education programs for elementary science.[2] These universities are scattered evenly across the nation and thus provide a good representation of the nationwide situation.

The analysis of the ratio of HPS/NOS-related in-service programs was made with the programs provided by eight major Offices of Education (of seven metropolitan cities and one province) among sixteen regional Offices of Education. Among the eight, Offices of Education in Seoul and in Gyeonggi Province cover nearly a half of the total population of the nation, while the remaining six Metropolitan Offices of Education are scattered across the nation.[3] Therefore, the in-service programs of the eight major Offices of Education provide a good representation of the whole nation.

67.5.1.2 Analysis Method

The analysis of preservice programs was carried out with the curriculum information shown on the universities' home pages in 2011. The titles and credits of the courses which appeared to be HPS/NOS-related were identified, and the ratios of the credits of the courses out of the total credits for a successful completion of the degree (i.e., B.Sc.) were calculated. Since the information used in the analysis was obtained from university home pages, the actual practice in the universities might be somewhat different from the data obtained in this study.

Similarly, the analysis of in-service programs was carried out based on the information obtained from the home pages of the Offices of Education. Generally, there are two kinds of in-service programs: one conducted directly by the Office of Education or its official in-service training institution and the other conducted usually by schools or teacher associations or private sectors. While the former is listed in the science education plan of the Office of Education, the latter is often classified as the specialized institutions' in-service programs. For each Office of Education, the whole in-service programs were first checked, and among them science programs and HPS/NOS-related programs were identified based on their titles. During this process, in order to focus on science or science education programs, programs for teachers' general qualifications, gifted education, environment, invention, and visiting from domestic or foreign universities were excluded.

Offices of Education provide the information of their in-service programs with different levels of classification, some with broader classifications while others with narrower classifications. Thus it would be impossible to directly compare the numbers of programs provided by different Offices of Education. As a result, the analysis of HPS/NOS-related in-service programs in this session is sensible only in terms of ratio compared with the whole programs of a particular Office of Education and any comparison in terms of its number between Offices of Education would be meaningless.

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[2] The names and URLs of the National Universities and of the National Universities of Education are listed in the Appendix.

[3] The names and URLs of the eight Offices of Education are listed in the Appendix.

Table 67.11 Titles and credits of HPS/NOS-related courses in the curricula of National Universities in Korea

University	Credits for graduation	Titles of HPS/NOS-related courses (credit)	%[a]
A	130	Historical Development of Physics Concepts (3)	5.4
		History of Science for Teachers (2)	
		Philosophy of Science for Teachers (2)	
B	140	History and Philosophy of Physics (3)	4.3
		Philosophy of Science (3)	
C	150	History of Earth Science and Inquiry Method (3)	2.0
D	150	History of Physics (3)	2.0
E	140	History of Science (3)	2.1
F	140	History of the Earth (2)	1.4
G	141	History and Philosophy of Science (3)	5.0
		Education of Earth History (3)	
		History of Chemistry (1)	
H	150	History of Chemistry and Chemistry Education (2)	7.3
		History of Earth Science and Earth Science Education (3)	
		History of Earth and Practice (3)	
		Philosophy of Science and Science Education (3)	
I	140	History of Physics and Philosophy of Science (3)	4.3
		History of Biology and Biology Education (3)	
J	140	History of Physics (3)	2.1
Total	1421		3.5

[a] The ratio of the credits of HPS/NOS-related courses to the total required credits for graduation

67.5.2 Results of the Analysis of HPS/NOS-Related Preservice Teacher Education Programs in Korea

Table 67.11 shows the ratios of the credits of HPS/NOS-related courses in the ten National Universities which provide preservice teacher education for secondary science.

As seen in Table 67.11, all ten National Universities which provide preservice teacher education for secondary science offer some sorts of HPS/NOS-related courses, such as “History of Science for Teachers,” “Philosophy of Science for Teachers,” and “History of Physics and Philosophy of Science.” However, about a half of the universities offer only one course of two or three credits. Only three of them offer three or more HPS/NOS-related courses. The average ratio of the credits of HPS/NOS-related courses to the total required credits for graduation was only 3.5 %. Although as seen earlier HPS/NOS-related papers and content in textbooks increased over time, teaching of HPS/NOS in preservice teacher education seems still not to be popular. This tendency is even more apparent in National Universities of Education, as shown in Table 67.12.

As shown in Table 67.12, only four National Universities of Education offer HPS/NOS-related courses, and among the four three offer only one course of two credits.

Table 67.12 Titles and credits of HPS/NOS-related courses in the curricula of National Universities of Education in Korea

University	Credits for graduation	Titles of HPS/NOS-related courses (credit)	%[a]
A	140	–	–
B	144	–	–
C	152	Science in Life and in History (2) Understanding Earth Science with History (2)	2.6
D	140	–	–
E	145	–	–
F	145	History of Science (2)	1.4
G	145	History of Science (2)	1.4
H	145	–	–
I	147	History of Science (2)	1.4
J	145	–	–
K	150	–	–
Total	1448		1.9

[a] The ratio of the credits of HPS/NOS-related courses to the total required credits for graduation

In sum, the average ratio of credits of HPS/NOS-related courses to the total required credits for graduation was only 1.9 %. Furthermore these courses are only optional, not mandatory. For example, in "G" National University of Education, there are 12 departments and only about a half of the students of science education department usually take the course of History of Science, implying that only about 5 % of the students of G National University of Education take the course of History of Science. Although this analysis was only based on the information shown at the universities' home pages, which might be quite different from their actual practice, and some HPS/NOS-related content can be taught in more general courses like "Theories of Science Education" or "Methods of Teaching and Learning of Science," the fact that only less than a half of the universities offer HPS/NOS-related courses clearly shows that the teaching of HPS/NOS in Korean National Universities of Education is very limited.

Tables 67.13 and 67.14 also show that the provision of HPS/NOS-related in-service programs is also extremely limited.

As shown in Table 67.13, out of a total of 130 programs appeared in the in-service training plans for science education of the eight Offices of Education, there were 72 science-related programs, and among them "History of Science for Teachers," provided for 32 teachers schedules for 15 h, was the only program related to HPS/NOS. Similarly, out of a total of 2083 programs in special institutions' in-service training programs provided by the Offices of Education, there were 81 science-related programs, and among them "Teaching Practice of Science Ethics Lessons," provided for 25 teachers scheduled for 30 h, was the only program related to HPS/NOS. Even considering the possibility that there would be some more programs which would include HPS/NOS-related content or activities, the HPS/NOS-related content or activities in Korean preservice as well as in-service teacher education programs are very much limited.

Table 67.13 HPS/NOS-related programs appeared in the in-service training plans for Science Education of Offices of Education

Office of Education	Number of the total in-service programs[a]	Number of science-related in-service programs	Number of HPS/NOS-related in-service programs (title, target group, participants, hours)	Year
A	42	18	1 (History of Science for Teachers, Secondary Science Teachers, 32 persons, 15 h)	2011
B	17	4	–	2011
C	16	12	–	2010
D	9	9	–	2011
E	14	8	–	2011
F	15	9	–	2011
G	4	3	–	2011
H	13	9	–	2008
Total	130	72	1	

[a] Since each Office of Education provides the information of its in-service programs with a different level of classification, it would be meaningless to compare the numbers of the programs provided by different Offices of Education

Table 67.14 HPS/NOS-related programs in special institutions' in-service training programs provided by offices of education

Office of Education	Number of the total in-service programs[a]	Number of science-related in-service programs	Number of HPS/NOS-related in-service programs (title, target group, participants, hours)	Year
A	1144	54	–	2011
B	160	7	1 (Teaching Practice of Science Ethics Lessons, K-12 Teachers, 25 persons, 30 h)	2011
C	111	1	–	2010
D	60	2	–	2011
E	264	5	–	2011
F	186	9	–	2010
G	55	1	–	2011
H	103	2	–	2011
Total	2083	81	1	

[a] Since each Office of Education does or does not provide the information of its in-service programs done by special institutions, it would be meaningless to compare the numbers of the programs provided by different Offices of Education

67.6 Conclusion

In this chapter, the status quo of HPS/NOS-related aspects of Korean science education was outlined. To do this, the historical changes of Korean National Science Curricula were summarized. Then the change of research trends of science education by analyzing the HPS/NOS-related papers published in JKASE for the last three decades was examined. After that the HPS/NOS-related aspects in science textbooks and in the programs of (preservice and in-service) science teacher education were analyzed.

Since the middle of 1980s, science in Korean National Curriculum began to have more of concrete and expressive descriptions related to HPS/NOS. The 5th National Science Curriculum announced in 1987 included "scientific literacy" as one of its major objectives, while the 6th National Science Curriculum announced in 1992 emphasized STS-related content and instruction methods. 2007 National Science Curriculum included once again "scientific literacy" as its one of major objectives and suggested to use materials related to scientists, the history of science, and to science-related or socio-scientific issues.

The analysis of the papers published in *Journal of Korean Association for Science Education* (the most representative academic journal of the field) for the last three decades shows that there has been a continuous substantial body of HPS/NOS-related studies on the areas, such as HPS/NOS-related recognition and ideas, instruction methods or programs, and the nature and features of terms or concepts. Although in general science education research in Korea has been more inclined to some specific areas (such as, quantitative studies, review studies, studies on students' or teachers' HPS/NOS-related perceptions or attitudes), recently studies with more diverse research purposes or methods or new perspectives or new theories became more popular.

The HPS/NOS-related content in Korean science textbooks for G3–G10 appeared to be biased in areas like the descriptions of scientists, the evolution of science, material of historical content, scientific method, and the developmental model of scientific knowledge and in terms of the purposes or roles in science education. However, the newly introduced sections (such as "Science Stories," "Inquiry by Scientists," "Free Inquiry") in the 2007 National Science Curriculum encouraged more and diverse HPS/NOS-related content in the textbooks.

The analyses of the HPS/NOS-related courses or programs in preservice and in in-service teacher education programs showed that there is a need to have more programs related to HPS/NOS both in preservice as well as in-service programs.

Based on the findings of the analyses reported in this paper, the following implications to Korean science education can be made.

Firstly, there is a need to have a continuous emphasis and concrete guidelines for HPS/NOS in the National Science Curriculum. As we have seen in the analyses of research papers in *JKASE* and of science textbooks, the National Science Curricula have played important roles in encouraging relevant studies and in including related content in textbooks. Especially, in a nation like Korea where a centralized education system is firmly placed, the inclusion and concrete descriptions of HPS/NOS aspects in the National Science Curriculum are vitally important in bringing real changes in research activity, in textbook content, and in teacher education programs. Although this cannot be the sufficient condition, it would be a necessary condition or an effective way for the actual change.

Secondly, there is a need to apply a wide range of methods and tools of research. As seen earlier, HPS/NOS research activities in Korea have been influenced by the available research methods and tools of the time. For example, the increase of studies on students' or teachers' perceptions or attitudes around the 1990s was possible by applying newly developed tools like TOSRA, VOSTS, DAST, and Nott and Wellington's. On the other hand, the increase of qualitative studies in Korea was affected by the worldwide trend of qualitative studies. Recently, Lederman (2007) began to combine the NOS survey tool with the qualitative approach, thus is expected to produce more comprehensive research results. In addition, since research results are influenced by their sociocultural backgrounds, the development of research tools, especially revised or newly developed in connection with Korean sociocultural context, would provide more meaningful and comprehensive results for HPS/NOS-related studies.

Thirdly, there is a need to develop and to put into practice more HPS/NOS-related programs for preservice and in-service science teachers. HPS/NOS-related programs for preservice and in-service science teachers in Korea have been insufficiently provided, especially for elementary science teaching. According to the study of Lee and Shin (2011) which carried out a survey with specialists of science education and of the history of science, the most common responses to "why is the history of science not used actively in schools?" were "no sufficient appropriate materials for teachers in schools," "teachers' ignorance of how to use the history of science," "no proper preservice education programs for the usage of the history of science," and "no proper in-service training programs for the usage of the history of science." In order to have more active teaching and learning of HPS/NOS in school education, not only its emphasis in the National Science Curriculum and in science textbooks, the development and implementation of HPS/NOS-related preservice and in-service programs are needed.

Fourthly, there is a need to have comparative studies across nations. Although in this chapter the findings of National Science Curricula, science textbooks, and teacher education programs of Korea were loosely compared with related international trends, the discussion was very limited due to the lack of the authors' understanding and information of the world trend and cases of other nations. Further studies addressing this comparative analysis are in need. In particular, regions in East Asia where much of the educational system and school practice is shared would be the easiest and should be the first area to be targeted in this kind of comparative studies.

Finally, there is a need to develop the collaboration between the communities of science education and science studies. HPS/NOS is the very area where the two (or more) different academic communities need to work closely. However, it is in fact true that the two different communities have rarely shared their expertise and experience. Perhaps like in many other countries, in Korea, many of science educators frequently refer to the theories and concepts of the history, philosophy, and communication of science but with little relevant professional training, while the historians and philosophers of science have strong interest in science education but with no relevant experience. Together with today's great demands for informal science education, PUS (public understanding of science), and science culture, the active communication and collective efforts between the two communities are called for more than ever before. In this respect, the activity of IHPST (International History, Philosophy, and Science Teaching group) and its regional activities (like 2012 IHPST Asian Regional Conference) are with high expectations.

In this chapter, the authors focused on describing the recent and current situations of HPS/NOS-related aspects in Korean science education. Thus, due to some practical reasons, it was inevitable not to discuss the issues in depth and to cover the whole range of related issues. Despite all these limits, it is hoped that this chapter will help the readers to better understand some aspects of Korean science education, in particular those related to HPS/NOS.

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Appendix

Textbooks Selected for the Analysis in the Study

G3-1: Ministry of Education, Science and Technology of Korea (2010). *Science 3–1*. Kumsung, Seoul.
G3-2: Ministry of Education, Science and Technology of Korea (2010). *Science 3–2*. Kumsung, Seoul.
G4-1: Ministry of Education, Science and Technology of Korea (2010). *Science 4–1*. Kumsung, Seoul.
G4-2: Ministry of Education, Science and Technology of Korea (2010). *Science 4–2*. Kumsung, Seoul.
G5-1: Ministry of Education, Science and Technology of Korea (2011). *Science 5–1*. Kumsung, Seoul.
G5-2: Ministry of Education, Science and Technology of Korea (2011). *Science 5–2*. Kumsung, Seoul.
G6-1: Ministry of Education, Science and Technology of Korea (2011). *Science 6–1*. Kumsung, Seoul.
G6-2: Ministry of Education, Science and Technology of Korea (2011). *Science 6–2*. Kumsung, Seoul.
G7-A: Kim et al. (2010). *Middle School Science 1*. Doosandonga, Seoul.
G7-B: Lee et al. (2010). *Middle School Science 1*. Kumsung, Seoul.
G8-A: Kim et al. (2011). *Middle School Science 2*. Doosandonga, Seoul.
G8-B: Lee et al. (2011). *Middle School Science 2*. Kumsung, Seoul.
G9-A: Kim et al. (2012). *Middle School Science 3*. Doosandonga, Seoul.
G9-B: Lee et al. (2012). *Middle School Science 2*. Kumsung, Seoul.
G10-A: Jeon et al. (2011). *High School Science*, Mirae N, Seoul.
G10-B: An et al. (2011). *High School Science*, Kumsung, Seoul.

National University (Secondary Education) Selected for the Analysis in the Study

Chonbuk National University (http://www.jbnu.ac.kr/)
Chonnam National University (http://www.jnu.ac.kr/)
Chungbuk National University (http://www.chungbuk.ac.kr/)
Gyeongsang National University (http://www.gnu.ac.kr/)
Jeju National University (http://www.jejunu.ac.kr/)
Kangwon National University (http://www.kangwon.ac.kr/)
Kongju National University (http://www.kongju.ac.kr/)
Korean National University of Education (http://www.knue.ac.kr/)
Pusan National University (http://www.pusan.ac.kr/)
Seoul National University (http://www.snu.ac.kr/)

National University of Education (Primary Education) Selected for the Analysis in the Study

Busan National University of Education (http://www.bnue.ac.kr/)
Cheongju National University of Education (https://www.cje.ac.kr/)
Chinju National University of Education (http://www.cue.ac.kr/)
Chuncheon National University of Education (http://www.cnue.ac.kr/)
Daegu National University of Education (http://www.dnue.ac.kr/)
Gongju National University of Education (http://www.gjue.ac.kr/)
Gwangju National University of Education (http://www.gnue.ac.kr/)
Gyeongin National University of Education (http://www.ginue.ac.kr/)
Jeonju National University of Education (http://www.jnue.kr/)
Seoul National University of Education (http://www.snue.ac.kr/)

Office of Education Selected for the Analysis in the Study

Busan Metropolitan City Office of Education (http://www.pen.go.kr/)
Daegu Metropolitan City Office of Education (http://www.dge.go.kr/)
Daejeon Metropolitan City Office of Education (http://www.dje.go.kr/)
Gwangju Metropolitan City Office of Education (http://www.gen.go.kr/)
Gyeonggi Provincial Office of Education (http://goe.go.kr/)
Incheon Metropolitan City Office of Education (http://www.ice.go.kr/)
Seoul Metropolitan Office of Education (http://www.sen.go.kr/)
Ulsan Metropolitan City Office of Education (http://www.use.go.kr/)

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Chapter 68
History and Philosophy of Science in Japanese Education: A Historical Overview

Yuko Murakami and Manabu Sumida

68.1 Precursors

68.1.1 Science and Technology in the Edo Period

68.1.1.1 Under the Isolation Policy

Japan developed its own science and technology during the Edo period (1600–1867). At the time the government countered colonization efforts by Christian ministries by adopting a policy of national isolation (1633–1854) and by banning Christianity (1587–1858). Diplomatic ties were, however, continued with Korea, the Netherlands, and China. Such ties were nonetheless still regulated by the government. Some translators did manage, though, to import scientific knowledge from the Western world. For example, the Dutch version of Johan Adam Kulmus's *Anatomische Tabellen* was translated into Japanese (1774) with illustrations by Odano Naotake (1750–1780).

Scholars are still examining the philosophical foundations of science in the Edo period. Some principal figures in scientific thought in the period include Arai Hakuseki and Miura Baien. Tsuji (1973) points out the roles of neo-Confucianism combined with rationalism in shaping the nature and practical emphasis of Edo science where articulating the laws of nature was connected to social justice. Nakayama (1977), by contrast, argues that the influence of Chinese thought on the understanding of

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scientific laws was political: if observation did not fit a theory, it was considered an omen requiring governmental response. There is thus no consensus on the influence of Confucianism upon Japanese science.

Research in astronomy, initially imported from China, was conducted to develop the locally adjusted calendar system for Japan. Shibukawa Harumi became the first official astronomer in 1685 responsible for a Japanese calendar. The astronomy office dealt with the importation of all scientific knowledge, including maps and translations from the Dutch. This office became the Bansho Torishirabesho, one of the origins of the University of Tokyo.

Wasan, or Japanese mathematics, was developed independently from Western mathematics. Seki Takakazu (1642–1708) discovered differentiation and developed an equivalent of Bernoulli numbers, an approximation of pi, and trigometric functions.[1] Wasan was widely accepted in Japanese society before the Meiji restoration as a form of entertainment. People from various social classes donated wasan problems to temples and shrines.

Interest in wasan reflected the notable literacy rate of the Edo period even in the general public. It is said that 50 % of males and 20 % of females were literate nationwide in late Edo period. Generally speaking, the public was eager to learn to read and write and to perform basic calculations with an abacus. Literacy of this kind was facilitated by thousands of small private schools open to the general public.

Almost everyone in the Samurai class was literate. The government operated various kinds of schools for elites. Shoheizaka Gakumonsho in Edo (current Tokyo) was the main school, which aimed to teach Confucianism. It later developed into the Kaiseisho, which in turn merged with the University of Tokyo. There were also schools for the study of China, medicine, and foreign languages. Each local government also had a school. Altogether there were 270 governmental schools in the late Edo period.

68.1.1.2 Tension Between Nationalists on Science and Technology

Discussion on Japanese isolation ended when war vessels of Russia, the British Empire, France, and the United States approached Japan (1787–1854) to negotiate unilateral treaties, forcing Japan to open its borders. Nationalists argued for “Western technology with the Japanese mind (和魂洋才),” while advocates for opening the country coined the slogan “Secede from Asia and join Europe (脱亜入欧).” Both parties recognized that Western technology and scientific knowledge were the keys to avoiding colonization and maintaining national independence. The tension between nationalists who favored isolationism and those who insisted on opening the country continued for a long time.

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[1] Research on the meaning of wasan is ongoing. The concept, to date, has been largely misunderstood. For example, some argue that wasan lacks the notion of functions (Ueno 2006).

68.1.1.3 Technology Transfer from Europe Around the Meiji Restoration (1862–1880)

Western technology was imported to some regions in the end of Edo period. Satsuma (current Kagoshima area) introduced British cotton and sugar industries, for example. Technology transfer was extended after the Meiji restoration (1868). The Japanese government then took steps to import Western technology and scientific knowledge.

The foundation for a strong emphasis on engineering was laid by a younger generation that studied abroad before the restoration, such as the "Choshu five," five young samurais who left Japan illegally in 1862 and smuggled themselves to England in 1863. Kido Takayoshi, who was one of the main actors of the Meiji restoration and later became an important figure of the new government, supported their travel. Jardine Matheson & Co. arranged their stay in London. They first learned English and then began studying in the University College of London. Among the five students, Ito Hirobumi and Inoue Kaoru went back to Japan earlier than the other three when Choshu's fight against Europe was reported on a newspaper in 1864. They became important figures in the new government: Ito Hirobumi became the first minister of industry in 1876; and Inoue Kaoru became the second minister of industry. The other three continued their study in England. Endo Kinsuke followed them due to health problem in 1866. Inoue Masaru learned railroad systems in London. Yamao Yozo, interested in shipbuilding, moved from UCL to Glasgow. He worked at Napier shipbuilding in the daytime and studied at Anderson College at night. He met Henry Dyer there, who later came to Japan where he became the first chairperson of the new school of industry. Yamao and Inoue were called back to Japan in 1868.

It was not only Choshu who sent students abroad. Satsuma sent 19 students to England in 1865 with full financial support from the Satsuma feudal government. The Edo government also sent 17 students to study abroad with Enomoto Takeaki as its leader; he later became an admiral. Most of the students were naval cadets, but Nishi Amane and Tsuda Mamichi received training in law and political science in the Netherlands. They left Edo in 1862 and arrived at Rotterdam in 1863. Nishi and Tsuda went to Leyden and attended lectures of Simon Vissering and Cornelius Willem Opzoomer. They went back to Japan via Paris in 1865, where they met other intellectuals and the future political leaders of Japan. One of them was Mori Arinori, who later became the first minister of education in the Meiji government.[2]

After their arrival, Nishi and Tsuda were assigned to Kaiseisho, the main school of the Edo government. Kaiseisho merged with the University of Tokyo after the Meiji restoration. Nishi and Tsuda became government officers and translated many academic books as well as developing their own original philosophy. It was a critical time for Japan to integrate Western ideas to the native Japanese framework of thought. The words "Kagaku" and "Tetsugaku" were coined by Nishi to mean "science" and "philosophy."

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[2] See Piovesana (1963).

"Kagaku" is most widely used as a general term for "science." The word "Kagaku" literally means "section-study," which reflected the Western propensity to develop specialized scientific fields in the late-nineteenth century. The literal meaning may even have precipitated sectionalism in the development of science and technology in Japan.

The word "science" is currently translated into four different words, "gakujutu," "kagaku," "rika," and "rigaku." "Gakujutu" is almost similar to academic activities or the Latin word *scientia*. "Kagaku" can be paralleled with "shakai" (society) or "gijutu" (technology) as general terms, where "rika" and "rigaku" sound inappropriate. "Rika" is currently used for the name of subject in elementary and secondary education, while "rigaku" is used for the academic area of natural science in higher education in the same level as "kogaku" (engineering) or "hogaku" (legal science). A difference is that "rigaku" often includes mathematics, while "rika" does not. "Rika" as an academic subject covers physics, chemistry, geology, and biology.

The word "rika," however, appeared first as the name of an academic field in the same level of "bunka" (humanities) and "ika" (medical), the same as the current use of "rigaku." Thus, "Rika Daigaku" meant the college of science in the early modern period of higher education in Japan. The first Education Law (教育令) (1879) specified physics, physiology, and natural history as optional subjects, i.e., the word "rika" appeared only to indicate one of specialized areas in higher education.

The word "rika" was then introduced into primary and secondary education in an 1886 ordinance of ministry of education (Ministry of Education 1986) following an 1885 amendment to educational law. The ordinance was the first official curricular guideline, and it specified "Rika" as an educational subject in upper elementary school. The contents were not explicitly stated, but the emphasis was placed on scientific phenomena in everyday life.

Such multiple meanings for the Western term "science" are indicative of the conceptual struggles at stake in adapting ideas and concepts from the Western world in Japan.

68.2 Science and Technology in the Meiji Period

68.2.1 Institutionalization of Education in Science and Technology

After the Meiji Restoration (1868), the new government was eager to introduce Western science and technology in order to maintain national independence in an age of imperialism. This decision was for the most part successful, but it neglected NOS.

The ministry of education was established in 1870. In 1871 it announced a plan for 4-year lower elementary schools, 4-year higher elementary schools, middle schools, and universities. Despite the ambitiousness of their plan, only elementary schools were inaugurated, with the number of schools growing to 26,000 within a few years. Although the ministry of education set the curriculum, most elementary schools taught only basic writing, reading, and calculation as they had in the Edo period because most teachers were unable to instruct in much more. In 1882 the ministry of education changed the initial educational system by dividing elementary schools into three levels: 3 years for the first stage, 3 years for the second stage, and 2 years for the last stage. Science was taught from the second stage onward. The first 4-year education became compulsory in 1887. The school attendance rate was about 50 % at that time and grew to more than 99 % by 1917. The majority of the population did not attend school beyond what was compulsory, however. Those who learned science, therefore, were of a relatively small number due to the position of the subject in the curriculum.

The number of middle schools grew only slowly. Curriculum guidelines for middle schools were published by the ministry of education in 1882. There were vocational-oriented middle schools and academic-oriented middle schools.

Governmental examination of school textbooks began in 1887 in order to determine compliance with national standards. This textbook examination system continues to the present.

68.2.2 The School of Engineering and the Imperial University of Tokyo

The establishment of a modern university was a main goal of late-nineteenth century educational reforms. Only one university, though, was launched by 1877 following the 1870 law governing university education. Its predecessor was the school of European culture the Edo government had established in 1855.

The basic idea behind the higher education was nationalistic. The first item of the Imperial University Law explicitly stated that Imperial Universities were for teaching and research in the arts and sciences to meet the country's needs (帝国大学令第一条　帝国大学ハ国家ノ須要ニ応スル学術技芸ヲ教授シ及其蘊奥ヲ攷究スルヲ以テ目的トス). It envisioned the Imperial Universities as contributing to national power and prestige through practical research and basic science. Consequently, certain dimensions of NOS were not emphasized, and Western notions of science and technology were still in the process of being integrated into the Japanese conceptual framework for science education.

The University of Tokyo began offering courses with four schools in 1877: the schools of law, literature, science, and medicine. The school of science had opened in 1876 with ten departments: mathematics, physics, chemistry (basic chemistry and applied chemistry), biology (zoology and plant biology), astronomy, engineering (mechanical engineering, civil engineering), and mining. Emphasis was placed on applied science and engineering at first.

With a ministry of industry opening in 1870, a school of engineering opened in 1873 before the University of Tokyo. The school of engineering began to offer classes in 1875. Yamao Yozo advocated national educational institutions of engineering.

An elementary school of industry was also proposed but unrealized. The ministry of industry planned to hire a chairperson and six lecturers from industrialized Scotland; in the end nine lecturers were hired. Henry Dyer, who learned mechanical engineering in Anderson College in Glasgow, came to Tokyo to work as the chairperson of the new school of industry in 1875 when he was 25.

Dyer crafted the school's mission: an institution with a comprehensive coverage of engineering. Thus, the school had seven departments from the beginning: civil engineering, mechanical engineering, architecture, electronics, chemistry, metal engineering, and mining. Each department offered both theoretical and practical aspects of its field. The school had a 4-year course of study, each with a modest tuition fee of ten Japanese Yen a year. Excellent students were sent to Europe after graduation.

The four departments of engineering and applied science at the University of Tokyo were separated from the school of science in 1885 to be merged with the school of engineering of the Imperial University of Tokyo and the school of engineering earlier established by the ministry of industry. Those lecturers from Scotland moved to the Imperial University of Tokyo. The school of science of the Imperial University of Tokyo had seven departments: mathematics, astronomy, physics, chemistry, zoology, plant biology, and geology. It also had a research institute of marine science and a school of agriculture. The schools of engineering and agriculture were intended to promote industry, while the school of science concentrated on basic science.

The Imperial University then invited more lecturers from European countries, while young Japanese elites were sent to European countries to study industrial systems and scientific and technical knowledge. Some of them taught in universities after coming back to Japan, but most went to the government to establish social systems. Initially students of engineering were sent to England, but later more students went to the United States. Medical students along with students in the humanities, social sciences, and physics were mainly sent to Germany.

More Imperial Universities were established after Tokyo: Kyoto, Tohoku, Kyushu, and Hokkaido. Furthermore, educational institutes for engineers were established. Tokyo Institute of Technology was established in 1881 as the Tokyo Vocational School. The name was changed to Tokyo Technical School (1890) and later Tokyo Higher Technical School (1901). In 1929, Tokyo Higher Technical School was elevated to a degree-conferring University as Tokyo Kogyo Daigaku (Tokyo Institute of Technology). The introduction of history and philosophy of science and technology as subjects of instruction had been discussed since 1930s at Tokyo Institute of Technology, whose institutional model was Massachusetts Institute of Technology.

Private schools attracted students who wished to learn modern science as well as foreign languages. Tokyo professional school, which is the precursor of Waseda University, was established in 1882 with four schools: political science and management, law, science, and English. The school of science disbanded after 3 years, but a new school of science and engineers was established in 1908.

Fujiwara University of Engineering was the first private university dedicated to science and engineering. It was established in 1939 by Ginjiro Fujiwara, the first president of Oji paper manufacturing company. He intended to donate the university to his alma mater, Keio University. It eventually merged with Keio University as a school of science and engineering in 1944.

Due to the increasing number of institutions of higher education, the number of engineers continued to grow. There were 1,500 graduates from colleges and their equivalents in 1900; 5,000 in 1910; and 55,000 in 1934. These technical graduates found employment in the government as well as in industry. The transfer for technology government to industry began around WWI.

Still, NOS and HPS remained the exception rather than the rule in Japanese higher education. Tohoku University had a position of philosophy of science in the school of science. It also planned to have a permanent position for Japanese mathematics (wasan), but budgetary limitations did not allow for it. Only a wasan archive was introduced in the university library. Tokyo Institute of Technology had HPS positions; the tradition continues to the present as a part of the department of management engineering. Those positions were considered as part of a liberal arts education for scientists and engineers, but they were always secondary to specialized fields of science and engineering.

68.2.3 Nature of Science in Japanese Literature of the Meiji Period

Although nature of science was not widely taught in Japanese education in the Meiji and Taisho periods, there were popular novels and essays which dealt with nature of science.[3] They influenced Japanese ideas of science.

Terada Torahiko (1878–1935) was a geophysicist, essay writer, and haiku poet. He taught physics in the Imperial University of Tokyo and had studied in Berlin. At the same time, he was a core member of the literary community with Natsume Soseki. He published a number of popular essays whose main topic was nature of science. Terada criticized lectures at all educational levels that crammed knowledge of science into them. “When teaching science,” he argued,

> teachers must be most careful to nurture children’s minds for research. That goal is not reached if they are merely given pieces of knowledge. Today even university students who are science majors are not motivated to do research by themselves. Their knowledge tends to be superficial. So it seems that they remember from their education in elementary schools to be content only with remembering knowledge (Terada 1918, p. xx).

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[3] The importance of popular culture in public’s interest in science in Japan continues to the present. The atomic bomb case before and after WWII was discussed in detail in Ito (2010), for example.

Terada was close to Ishihara Jun (1881–1947), a physicist. Ishihara studied physics under Einstein at Zurich Institute of Technology in 1914 and taught in Tohoku University, where he resigned due to love affair in 1921. He then became a professional author of NOS topics to gain popularity from a wide range of audiences. When Einstein came to Japan in 1922, Ishihara served as an interpreter. He published many popular articles in which he emphasized the analysis of observations and experimentation in terms of quantification and measurement as an effective means of dealing with abstractions and new phenomena (Ishihara 1936).

68.2.4 Ashio Copper Mine Accident (1885–current)

The Ashio copper mine accident turned into a social movement that changed opinions about the value of Western science. The mine was discovered in 1550, and its operation began 1610. Its production decreased after the early seventeenth century, but the Edo government kept it open. After 1877 when its ownership moved to Furukawa Ichibei, its production grew drastically with modern technology. The amount of sulfur dioxide produced during the refinement process jumped up, and the surrounding environment was heavily polluted by 1890. Polluted water contaminated crops in widespread areas.

The pollution accident was the first civil movement against the government's role in producing pollution in Japan. Tanaka Shozo, a politician of the affected area, led residents to demand compensation from the government. They also wanted the government to stop mining in Ashio. The government kept the mine open, however, due to the first Sino-Japanese War (1894–1895), the Russo-Japanese War (1904–1905), and WWI (1914–1918).

68.2.5 Impacts of WWI to NOS in Japan

Technology was transferred from the governmental sector to industry during WWI in Japan. Scientist and engineers from universities were assigned to the industrial sector as production shifted for wartime needs. As the war escalated the government planned domestic centers for research and development. In 1917 RIKEN was established. It was the first comprehensive research institute of basic and applied science in Japan. While practical goals were emphasized due to the government's policy of industrialization, RIKEN also devoted considerable resources to basic science. It supported Japanese physicists in international research in quantum physics and particle physics especially between 1925 and 1950.

The physicist Nishina Yoshio (1890–1951) built the first cyclotron in Japan (the second in the world) at RIKEN in 1937 for nuclear physics and its application to radioisotopes in medicine and biology. Research in nuclear physics was connected to potential military applications of atomic energy: Japan's atomic bomb program in

WWII was located at RIKEN. The development of uranium mines in Japan began in 1938, but mining ended after the WWII. Nuclear development resumed for non-military purposes in 1954 as a result of the "Atoms for Peace" program. The first postwar uranium mine in Japan, the Ningyo Toge mine, opened in 1955. It produced uranium until 1987, but the amount was not enough for practical uses.

68.2.6 Kyoto School of Philosophy

The Kyoto school of philosophy,[4] represented by Nishida Kitaro (西田幾多郎) and Tanabe Hajime (田辺元), argued for the close relationship of science, technology, and philosophy. Under the influence of neo-Kantian philosophy,[5] this school developed the philosophical position that science and philosophy have connections to an epistemology based on Zen Buddhism and Husserl's phenomenology. Nishida's main work, *An Inquiry into the Good* (1911), includes an acknowledgement of the restricted nature of science as a form of knowing: "A scientist's way of explanation is slanted toward just one aspect of knowledge, whereas for a complete explanation of reality we must satisfy intellectual demands as well as the demands of feeling and the will" (Nishida 1911, p. 50).

The school of science at Tohoku University was one of the few that regularly offer courses in NOS/HPS, a practice it continued until the 1990s. Philosophers took the lead in the early period. The first lecturer of NOS was Tanabe Hajime. He began his career in the school of science at Tohoku University after graduating from the University of Tokyo. He taught NOS there and published *Saikin no Sizenkagaku* (*Recent National Science*) (1915) and *Kagaku Gairon* (*Outline of Science*) (1918). He also translated Poincare's *La Valeur de la Science* into Japanese (1916).

He moved to Kyoto and succeeded Nishida's position.[6] There he published *Suri tetsugaku kenkyu* (*A Study of Philosophy of Mathematics*). His held two views of the philosophy of science (Sawada 1997), but both were different from present notions. The first was a collection of scientific approaches to philosophy that included aesthetics and religious studies; the second was the idea that the philosophy of science was part of a philosophy whose subject was science. In the latter sense he wrote: "Science today . . . has reached the stage where scientific theory has gone beyond the position where its subjects are the entities and existents dealt with in science. Science is now in the position to realize things beyond philosophy. Science has become philosophy; philosophy is a subject to be described in a scientific theory.

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[4] The development of HPS in Japan in its current sense is almost absent in the Kyoto School, as the school was accused of contribution to the Japanese navy after WWII.

[5] Manuscripts of Nishida and Tanabe can be examined online at the Kyoto school archive. http://www.kyoto-gakuha.info/

[6] Tanabe's position in Tohoku was taken by the philosophers Takahashi Satomi and Miyake Goichi, both of whom studied under Edmund Husserl.

In fact the new quantum theory of physics represents such a state of knowledge" (Tanabe 1963, p. 285).

Tanabe's illustrations of quantum mechanics as well as Ishihara Jun's commentaries on the theory of relativity, where their intended audiences were the general public, inspired young Yukawa Hideki, who later specialized in particle physics.

68.2.7 Science Education and NOS During WWII

Every aspect of Japanese society turned to the wartime efforts during WWII. Education was no exception. The purpose of mathematics and science in elementary schools was stated in a nationalist way: "to train the ability to think precisely and process normal events and phenomena and to apply this ability to everyday practice and to nurture rational and creative mind in order to prepare for contributions to the prosperity of the nation." (通常ノ事物現象ヲ正確ニ考察シ処理スル能ヲ得シメ之ヲ生活上ノ実践ニ導キ合理創造ノ精神ヲ涵養シ国運ノ発展ニ貢献スル素地ヲ培フコト[7])

The possibility of an exemption from military service motivated students to study the natural sciences, engineering, and medicine even in the later stages of the WWII when university students of social science and humanities were still being ordered to the front lines.

Paradoxically, though, the word "scientific" became a code word for left-wing movements and so was banned under the wartime militarism. Discussions concerning the social meaning of technology went underground during the war and stayed there for some time after the war.

At the same time, Sogensha, an Osaka-based publisher, published a series of classics of science. It includes a Japanese edited version of the Unity of Science (*Einheitswissenschaft*) work, but it was neglected.[8]

68.3 Higher Education in Japan After the WWII

68.3.1 Reform of Education After the WWII

Before and during WWII, the notion of science had been distorted to emphasize its nationalistic aspects. Every activity turned to wartime efforts.[9] Japan's surrender in 1945 led to a restructuring of the entirety of Japanese society and largely along

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[7] Ministry of Education (1941).

[8] Sawada (1997), p. 3.

[9] Okazaki and Okuno-Fujiwara (1999) points out that the social systems of Japan during the WWII essentially continued after the war under different names.

American lines. The Japanese educational system, formerly shaped by the strong influence of the German educational system, was no exception. Reform was realized in the fundamental education act (1947), the school education law (1947), and the standards for establishment of universities (1956).

The reform was in fact an introduction of American educational system with some lead by CIE-GHQ. The Standards for the Establishment of Universities was announced 1949. The standard general education in universities as occurred in the United States—which required every student to take some courses in humanities, social sciences, natural science, language study, and physical education – was introduced to Japan. The main body of the instructors of general education, however, came from former high schools, while university professors had more power with governmental policy to enhance science and technology.

This idea of a standard general education included basic courses in the natural sciences, including for students of the humanities and social sciences. Specialists taught these natural science courses. In this context, NOS-like courses were welcomed by students in humanities and social science as courses requiring less background knowledge in the sciences.

Students studying science and technology jumped in national universities during the 1950s: the number of entering students in science and engineering increased from 142,546 in 1952 to 202,334 in 1957. Popularization of higher education in Japan occurred in the late 1960s, when baby-boomers approached college-entrance age. The number of first-year students in universities and colleges jumped up to 598,872 in 1975 from 273,098 in 1963.

While science and technology grew in national universities as a result of a concentration of investment by the ministry of education, private universities were established to meet the growing demands of higher education especially for majors of business and the social sciences. National and public universities focussed on engineering, natural science, and medical departments. Yet, each type of university – public and private – had comparable tuition and fees due to subsidies.

Many private universities did not include science and technology in their upper divisions, although they still had to offer natural science courses for students of the humanities and social sciences. They often hired historians of science for such courses on a budget smaller than that for researchers in science and engineering who required expensive laboratories and experimental equipment.

Research universities with schools of science and engineering did not put much emphasis on NOS. Scientists taught natural science courses for students of the humanities and social sciences in general education. They were not necessarily courses on NOS but basic introductory courses. Professors of the natural sciences in the upper division focussed on research more than education. The training of students in natural science and engineering emphasized research skills. This emphasis has not changed since the end of WWII.

University standards were revised in the Deregulation of University Act (taikoka) of 1992. The relaxation of regulations did not specify general education requirements, the student/faculty ratio, or the requirements for facilities. Most universities disbanded their general education divisions as a result of deregulation. Former general education teachers were moved to other departments or to a new faculty or stayed in general education. The number of universities electing retaining general education, however, was small. Hence, the number of teaching positions of general education has decreased because retired faculty members have not been replaced; the positions have moved to upper division. Faculty members appointed in the previous system (appointed in or before 1949) retired by 1992 due to age restrictions. Students are now not required to take any natural science courses, and NOS/HPS courses have been either taught by part-time lecturers or discontinued.

68.3.2 Yukawa on Science in Late-Twentieth Century in Japan

Science essays were popular even after WWII when the formal education system in Japan was under a total reform. Yukawa Hideki, a physicist and the first Nobel laureate of Japan (1949), committed himself to public awareness of science. His writings on NOS issues were influential.

For example, Yukawa (1945) asked:

> What should be done to promote science in Japan? There are two typical answers. One: practical research in short-term goals has been overemphasized in Japan; basic science should be stressed from now; for that, scientific mind must be nurtured; research and education of history of science, for example, will be effective. The other typical answer: science education has focused on theory without connection to the real world; knowledge of the facts are essential; students should act by themselves; they should first get accustomed to operate various machines although they may not fully understand principles. Those answers seem to be totally opposite. The direction of science education will be significantly affected which answer we think right.
>
> Then, what have we lacked? I would say, in short, we lacked "thought". This sort of consideration would arise various oppositions. Theoretical research and imagination will just have no relationship to sound development of science and no advantage on science. There actually are various thought in Japan. Native philosophy has grown in Japan. (Yukawa 1945, p. 10)

Yukawa was vocal in arguing against the military uses of atomic energy. He signed the Russell-Einstein manifesto in 1955 and attended the Pugwash conference in 1957. His thought on science and society resulted as the Yukawa-Tomonaga manifesto in 1979.

68.3.3 NOS/HPS Societies in Japan

Yukawa also set the stage for interdisciplinary discussion on NOS. He was one of the founders of the Japan Association for Philosophy of Science in 1954. The association publishes the Japanese journal *Kagaku Kisoron Kenkyu* (1954-) and the English journal *Annals of the Japan Association for Philosophy of Science* (1956-). The title of this association does not have the Japanese word for philosophy "tetsugaku";

its literal translation is “Association for the Foundational Studies for Science.” The reason of the name sometimes is said that some scientists did not like the word. Philosophers of science were unhappy. Uchii Soshichi explained:

> Thus, the Japan Association for Philosophy of Science started in 1954; but that was not the end of the matter. Many philosophers were frustrated. There were two groups, one with the name “American Philosophy Group,” the other with the name “Logic of Science Group;” and they decided to meet annually with the title “The Meeting for Philosophy of Science” beginning in 1957. And these meetings led, eventually, to founding another association, with the literal title of “Philosophy of Science” (in Japanese) in 1967; that is the Philosophy of Science Society Japan (PSSJ). Thus we now have two associations for philosophy of science, which is quite unusual in the world. And this reflects the relationship between philosophers and scientists in Japan. (Uchii 2002)

The Japanese Philosophy of Science Society partially overlaps with the Japan Association of Philosophy of Science in terms of memberships especially among philosophers. The latter covers analytic philosophy and philosophy in the English-speaking world in general.

Such a history led to the current situation of Japan, where HPS-related domestic academic societies currently are mixed. Most were established in the late-twentieth century and remain small to middle sized like other academic societies of humanities and social sciences in Japan. The History of Science Society Japan (1,000 members) was established in 1941 and publishes *Kagakushi Kenkyu*「科学史研究」 (Japanese) and its English journal *Japanese Studies in the History of Science* (1962), which was followed by *Historia Scientiarum* (1980-). It has offered seminars to the public since 1975.

Other national-level societies include the Japanese Society for Science and Technology Studies and the Japanese Society for the History of Chemistry. There are many other regional societies and societies of each area, such as industrial history.

68.3.4 Department of History and Philosophy of Science in the University of Tokyo

HPS was introduced to Japan as an interdisciplinary subject in the course of educational reform after the WWII by Professor Tamamushi Bun-Ichi, who visited the United States. At Harvard University in 1950, he found the strong influence of Alfred North Whitehead and George Sarton. The delegates including Tamamushi agreed that such an interdisciplinary field would be of strong social needs in restoration of the country.

Tamamushi launched the Department of History and Philosophy of Science at the University of Tokyo in 1951, as a part of trial to introduce general education in the upper undergraduate program. Another founding member was a biochemist-historian of science, Kimura Yuichi. Later the botanist-historian of science Kimura Yojiro and philosopher Omori Shozo joined. Omori was an assistant of Morton White at Princeton IAS in 1950s. Its graduate program was established in 1970.

Saegusa Hiroto (Yokohama City University) and Yajima Suketoshi (Tokyo University of Science) supported the inauguration of the department.

Nakayama Shigeru studied astronomy in the University of Tokyo and moved as a Fulbright scholar to the Department of History of Science at Harvard from 1955 to 1959. After obtaining his Ph.D. from Harvard, he went back to Japan to teach history of science at the University of Tokyo.

The HPS department in the University of Tokyo was the only institutionalized HPS department in Japan until 1993. The liberal arts section of Tokyo Institute of Technology also had philosophers and historians of science. Yoshida Natsuhiko, who translated Ayer's *Language, Truth, and Logic* into Japanese in 1955, was the main figure there to attract many students of a wide range of backgrounds from physics to management engineering.

There were other groups of philosophers of science in Japan, however.[10] For example, Ichii Saburo (1922–1989) was a philosopher of history with a physics background. He studied in University of Manchester and then studied under Karl Popper. He later adopted the British Marxist approach to history. After returning to Japan in 1954, he translated Bertrand Russell's work into Japanese. Another example is Sawada Nobushige (1916–2006), who taught philosophy of science in Keio University. He also studied at Harvard as a visiting scholar. He wrote a popular introduction to philosophy and did original research in epistemology and logic.

68.4 NOS/HPS in School Science (Rika) in Japan After the WWII

After World War II a national education standard was issued in 1947. Textbooks were authorized by Ministry of Education in accordance with the prescribed course of study. Teachers had to teach the recommended content. The course of study for elementary schools and junior high schools and the course of study for high schools have been revised eight and nine times, respectively.

68.4.1 NOS/HPS in the Early Postwar Period of School Science Education

After the war the 1947 national education standard, science was referred to as Rika. This nomenclature has not changed for the past half century. In the 1947 course of study, elementary schools and junior high schools were handled as a single unit. The initial stated purpose of science (Rika) was "to equip students with the following three qualities related to problems of the students' environments, so as to ensure that

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[10] Sawada (1997).

all people can live a rational life and can enjoy better lifestyles": (1) the ability to look, think about, and deal with things scientifically, (2) knowledge related to the principles and applications of science, and (3) an attitude oriented toward finding and promoting the truth and creating new things. The following 13 sub-purposes were also identified (Ministry of Education 1947):

1. An attitude of being familiar with nature and an interest in scientific works
2. The ability to observe objects and phenomena in the natural world
3. The ability to think in a logical way
4. The ability to use machines and instruments
5. An interest in cultivating living things with care
6. Health-maintaining habits
7. Perseverance, willingness to help others, the habit of pursuing scientific work or research on one's own will
8. A desire to follow the truth and seek out the unknown
9. The ability to read easy science books
10. Knowledge of major scientific principles and their applications, allowing one to better understand the property of surrounding things and the relationships between them
11. Knowledge of the harmony, beauty, and bounty of nature
12. Respect for the work of scientists
13. Preparations for advanced science learning and necessary occupational preparations

Fujii (2005a) makes the following argument regarding the initial postwar purpose of science (Rika) education. The Japanese people had endured poor food, clothing, and housing conditions during the difficult years during and following World War II. Because it was a major social goal to somehow overcome these hardships and improve their living conditions, science education took on the characteristics of "Science (Rika) of everyday living." Nonetheless, it is interesting that the world "kagaku" is frequently used in the list of the purposes of Rika and that goals like cultivating "respect for the work of scientists" were included among its purposes.

The preliminary course of study for high schools, published in 1948, included separate proposals for physics, chemistry, biology, and earth science but contained no descriptions related to the science as a whole or anything related to the nature of science (Ministry of Education 1948).

In the 1951 revision, the junior high school and curriculum was coordinated with the high school curriculum, emphasizing the integrated nature of junior and senior high school education. Thus, the following were included among the purposes of science (Rika): science as a method and the use of scientific methods to solve problems, scientific attitudes and habits, the role of scientists and science in promoting human welfare and the development of contemporary civilization, and cultivating respect for specialists. These phrases applied to physics, chemistry, and biology (Ministry of Education 1951).

In the revised course of study for elementary school science prepared in 1952, science courses were expected to convey basic ideas on the nature of science, including the reality of natural phenomena and the objectivity and universality of science. Simple examples, such as the life cycle of the tadpole, were recommended as exercises suited to convey these notions. Beyond recommending the content of courses, revisions to the curriculum also specified the need for elementary children to understand the argumentative qualities of scientific knowledge, which the reforms viewed as linked to the students' engagement in simple investigations, in making predictions, in conducting experiments, and in comparing results. In this way students came to understand, the reformers believed, not only the persuasive qualities of scientific knowledge but also how new knowledge was created and competing results reconciled (Ministry of Education 1952).

68.4.2 NOS/HPS in School Science During the High-Growth Period

Japan became an independent nation in 1952 and in 1957 became a new member of the international community by joining the United Nations. This move was accompanied by developments in science and technology, including the enactment of the Vocational Education Promotion Act in 1951 and the Science Education Promotion Act in 1953. Revisions made to the course of study for elementary schools and junior high schools in 1958 and for high schools in 1955 (Ministry of Education 1955) represented an important turning point that shifted the focus of science education in Japan toward the natural sciences.

The stated purpose of elementary school science (1958) included the term "natural scientific" rather than just "scientific," and in high schools (Ministry of Education 1955), two of the four science subjects (Physics, Chemistry, Biology, and Earth Science) were made mandatory (further revisions in 1960 made four of the following courses mandatory: Physics A and B, Chemistry A and B, Biology, Earth Science). With these revisions, which can be viewed as a shift toward natural science fundamentalism, the content related to NOS was eliminated from the purposes and content of the course of study. What remained were descriptions of the "methods of natural science." It was in this revision that the term "scientific inquiry (*tankyu*)" first appeared within the stated purposes of Science (Rika) in the course of study for junior high schools and high schools.

In the revisions made to the course of study for elementary schools in 1968 (Ministry of Education 1968), for junior high schools in 1969 (Ministry of Education 1969), and for high schools in 1970 (Ministry of Education 1970), which occurred in the middle of the high-growth period, systematic learning that conformed to the systems of natural science was steadily promoted, and the emphasis was placed on understanding scientific methodology and the process of scientific inquiry. Given that the four subjects listed above were mandatory in high school science programs, a "Basic Science (Kiso Rika)" introductory course was established to ease the burden of taking the more specialized courses later on. One of the stated goals of this course was "to teach the methods of science" and "to make students aware of the contributions that natural science has made to improving human welfare" (Ministry of Education 1970).

68.4.3 NOS/HPS in School Science Education During the Stable Growth Period

As both the positive and negative aspects of the high-growth period began to be revealed, Japanese society found itself facing a variety of social problems that directly affected education. In a period of material affluence and prosperity, the issue of the pressures placed on students and student overwork – both the result of strict national standards – surfaced. At the same, Japan's low birth rate emerged as a central social issue. The keyword in the revised course of study around this time consequently was "yutori" (relaxed/pressure-free).

In the 1977 revisions to the course of study for elementary schools and junior high schools, the purpose of science (Rika) was condensed into a highly simplified form and the total class hours devoted to science reduced. For example, the purpose of elementary school science was "To cultivate the skills and attitudes needed for exploring nature through observation and experimentation, to facilitate understanding of natural events and phenomena, and to cultivate a deep sense of appreciation for nature" (Ministry of Education 1977a). In junior high school, students in all grade levels had been required to take 4 h a week in science classes up to this point, but the requirement was changed to 3 h per week for first- and second-year students. It is important to note that at this time, the word "science (*kagaku*)" was eliminated from the stated purposes of school science (Rika) in the course of study for elementary schools and junior high schools (Ministry of Education 1977a, b).

In the course of study for high schools published in 1978, science courses were completely reorganized and a standard number of credits were established (Ministry of Education 1978). These were as follows: Science (Rika) I (4 units), Science (Rika) II (2 units), Physics (4 units), Chemistry (4 units), Biology (4 units), and Earth Science (4 units). Science I – which was established to cover the content students had to learn prior to junior high school and to prepare them for further advanced learning – became mandatory, but no NOS content was included in the subject.

On the other hand, the stated purpose of Science (Rika) II, which was newly established by this revision, was "to identify issues related to events and phenomena that can be seen in the natural world and related to historical examples of science; and through scientific inquiry, to teach the methods of science and to cultivate problem-solving skills." In this revision the history of science entered into the science curriculum through the examination of historical examples of important scientific discoveries that demonstrated how principles and theories were established. Because Physics, Chemistry, Biology, and Earth Science, as well as Science (Rika) II had been made elective courses, the number of students electing Science (Rika) II was not so high compared to the number of students electing other courses.

In revisions made to the course of study for elementary schools (Ministry of Education 1989a) and junior high schools (Ministry of Education 1989b) in 1989, when the Showa era gave way to the Heisei era and educational reform for the twenty-first century was just beginning, the stated purpose of science (Rika) included terms like "the cultivation of scientific ways of looking and thinking" and "science (*kagaku*)," but statements related to NOS were still absent. In junior high school science (Ministry of Education 1989b), an elective science course, offered once a week, was established, and efforts were made to allow students with a particular interest in or passion for science to engage selectively in scientific inquiry.

Following the trend among elementary and junior high schools, major changes were made to the 1989 course of study for high schools with regard to science (Rika). The basic policy was to "establish course diversity." This change occurred in an environment where there was little freedom of selection in science courses, and courses were not able to accommodate sufficiently differences in students' skills, aptitudes, and preferred plan of study (Fujii 2005b). Thus, 13 elective courses were established: General Science (Rika) (4 units), Physics IA, Chemistry IA, Biology IA, and Earth Science IA (2 units each), Physics IB, Chemistry IB, Biology IB, and Earth Science IB (4 units each), Physics II, Chemistry II, Biology II, and Earth Science II (2 units each) (Ministry of Education 1989c).

Content related to NOS/HPS was still covered in the General Science class, but it only appeared as the "Study of cases of experiments in scientific history," which was one of three items in a list of "Research Topics." Considering the scope and level of the content, it was noted that "regarding important discoveries in the history of science, students should learn about the process by which principals and theories are established through the repetition of experiments and review of the scientific literature." Miyashita (2006) proposed using an earth science textbook with emphasis of history on geology and NOS for high school students and first-year college students. His idea was that the history of plate tectonics – a twentieth-century discovery – gave students a good grasp of how geological ideas had developed and, by implication, how science operated. The textbook also covered topics of national importance, including astronomy during the Edo period and the development of seismology as a native Japanese science.

68.4.4 NOS/HPS in School Science Education in the New Century

The key phrase found in the revised course of study of 1998 (elementary and junior high school) and 1999 (high school), at the dawn of the new century, was "a zest for life (*ikiru-chikara*)." Schools were asked to cultivate in students a rich sense of humanity and the ability to learn and think on their own. While descriptions of the purpose of science at the elementary school and junior high school levels included the usual wording concerning "carrying out observations and experiments," it was emphasized that students would do so "with their own prospectuses" (Ministry of Education 1998a) or "with a sense of purpose" (Ministry of Education 1998b). While this wording emphasized active problem-solving by students, other sections also reflected a departure from the simple empiricism-oriented teaching methods through which scientifically appropriate knowledge was cultivated through verification and falsification (Kadoya 1998).

Subjects were again reorganized in the 1999 revisions to the course of study for high schools (Ministry of Education 1999). With regard to NOS/HPS, a Basic Science (Rika Kiso) class (2 units) was newly established, with the stated purpose mentioning "the relationship between science and human activity" and "the scientific inquiry and investigation of nature and the process of scientific development." In terms of content, the guidelines included references to the "beginning of science" and "scientific inquiry into nature and the development of science." They addressed the inquiry into the origin of matter, which ultimately led to the development of science, cell discovery and theories of evolution, the process of establishing ways of thinking about energy, and the Copernican theory and plate tectonics. Students were required to select two of the following courses: Basic Science (Rika Kiso), General Science (Rika Sogo) A and B (2 units each), Physics I, Chemistry, Biology I, and Earth Science I (3 units each). To enable students to gain a broader range of basic science skills, they were also allowed to include one or more of the following courses in their curriculum: Basic Science, General Science A, or General Science B. Basic Science was no longer included as an entrance examination subject.

At the same time the Science and Technology Basic Law was enacted in 1995. It called for Japan to be "a nation based on the creativity of science and technology." The justification for this legislation cited three expectations of science and technology (S&T) for the twenty-first century. Science and technology were expected to lead to creative, cutting-edge developments and the creation of new technologies; contribute to solutions to the various problems that humanity will face in the future, including environmental problems, food, and energy problems, and AIDS; and create new cultures related to human life, society, and nature. The Science and Technology Basic Law also contained references to science education. Chapter 5, Article 19 stated that "the nation should implement necessary policy measures to promote the learning of S&T in school and social education, to raise awareness of S&T and to disseminate knowledge of S&T, so that all Japanese people, including the young, have every opportunity to deepen their understanding of and interest in S&T."

The Fourth Science and Technology Basic Plan,[11] approved by the Cabinet in 2011 based on this law, called for Japan "to consistently and systematically nurture talented children to lead the next generation" and "to enhance the interest of children in science and mathematics starting in elementary and secondary education so as to increase the population of children interested in such subjects, and to identify talented children and develop their abilities." The Super Science High School Project undertook various efforts to cultivate student interest in science and technology based on plans created by each school, such as developing classes based on an independent curriculum, forming partnerships with universities and research institutions, and conducting research on issues that take advantage of local conditions. Launched in 2002, the budget for this project grew to more than three times its original size, and it is still growing.

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[11] Also see Sect. 68.5 of this chapter.

The 2008 version of the course of study for elementary schools and junior high schools continued to highlight the key phrase “a zest for life (*ikiru-chikara*)” but incorporated major reforms. Specifically, the number of classroom hours devoted to elementary school science was increased from 350 to 405 (MEXT 2008a). The number of classroom hours devoted to junior high school science was increased from 290 to 385 (MEXT 2008b). These changes were expected not only to increase the quantity of science content but to improve qualitatively the process of scientific inquiry through the introduction of observational experiments and report writing by students. Emphasis was once again placed on the connection between science and everyday life. In the 2009 version of the course of study for high schools (MEXT 2009), “Science (Kagaku) and Our Daily Life” was established as the subject equivalent to the former “Basic Science (Rika Kiso),” and course names that included the word “General” were eliminated. The curriculum now consisted of Basic Physics, Basic Chemistry, Basic Biology, and Basic Earth Science (2 units each), and Physics, Chemistry, Biology, and Earth Science (4 units each) (MEXT 2009).

The purpose of the Science (Kagaku) and Our Daily Life subject was “to understand scientific view and methods and to inspire interests in science via experiences of observation and experiments of phenomena in everyday life in a fashion fit for the needs of vocational high school students.” History and philosophy of science were thereby eliminated from the official school curriculum of Japan, and science had only weak connections to other subjects. The course content was divided into three major segments: the development of science and technology, science in everyday life, and science and everyday living in the future. Students could either (1) take two of the following subjects, as long as one of them is Science and Our Daily Life: Science and Our Daily Life, Basic Physics, Basic Chemistry, Basic Biology, and Basic Earth Science or (2) take three of the following classes: Basic Physics, Basic Chemistry, Basic Biology, and Basic Earth Science.

University entrance examinations have excluded NOS/HPS-related content in favor of focusing on specialized subjects. The National Center for University Entrance Examination again announced in April 2011 that its examinations would not include “Science (Kagaku) and Daily Life” because that topic now appeared too general for high school instruction. As a result, high schools evaluated by the number of students accepted to prestigious universities would probably elect to eliminate NOS/HPS in order to spend more time on subjects considered to fit to entrance examinations.

This revision moved Japanese science education away from what was intended in the immediate postwar period, which at the elementary school level addressed the basic idea of science and at the high school level had taken up the systematic nature of natural science. Given that contemporary society is grounded in science and technology and the world has become a place where scientific knowledge is becoming increasingly globalized and technologies developed through continuous innovation, it is important for all people, regardless of gender or age, to have a wide range of knowledge of science and technology, as well as flexible ways of thinking and making decisions. This development may be called neo-scientism in the school science of the twenty-first century.

68.5 The Science and Technology Basic Plans and Their Impacts on NOS

The Science and Technology Basic Law (1995) led the Japanese government to issue four Science and Technology Basic Plans (1996–2000, 2001–2005, 2006–2010, and 2011–2015), which aimed to enhance the roles of science and technology in Japanese society. Each included NOS components, with foci on public awareness of science and enforcement of school science.

68.5.1 The First Science and Technology Basic Plan

The first Science and Technology Basic Plan, issued in 1999, lamented the public's low esteem of science and technology. So the first plan was designed to "gain the public's deep and broad understanding for the promotion of science and technology with full respect towards harmony with humans, society, and nature" by implementing government measures to improve public understanding of science and technology, a task for which they expected the cooperation of specialists in the production of "easy-to-understand information on science and technology" (pp. 14–15).

The first basic plan targeted the improvement of science and technology education in school education by focusing on teaching methods and new facilities, such as computer-aided learning facilities, as well as by emphasizing the practical aspects of science and technology (p. 42). A National Museum of Emerging Science and Innovation (*Kagaku Miraikan*) was established in 2001 in the framework of this basic plan for science and technology as the center for promoting science and technology. NOS/HPS content did not appear in the first basic plan, though.

Independently of the basic plan, the Japan Accreditation Board for Engineering Education was established in 1999 for accrediting engineering programs complying with international standards of engineering certification. As the international standard for engineering education includes an ethics requirement, universities which intended to offer JABEE-accredited programs were forced to introduce engineering ethics courses. The impact on NOS/HPS was limited, however. Most "ethics" courses were dedicated to practical aspects of engineering, such as compliance with regulations or general workplace ethics as a part of the social accountability and responsibility of engineers. Only a few programs invited NOS/HPS researchers to include other dimensions of science and technology in the curriculum.

The Japanese Society for Science and Technology Studies was established in 2001. Kobayashi Tadashi, the first president of the society, remarked in the prospectus of the society that twenty-first century technoscience entailed sociopolitical and philosophical challenges. He pointed out that the

> uncontrolled production of artificial goods is fast overwhelming the natural world, aggravating an already precarious environmental crisis; developments in biotechnology and information technology threaten the survival of traditional lifestyles and value systems. Human societies and individuals need to rethink their relationship with technoscience. (Kobayashi 2006)

68.5.2 The Second Science and Technology Basic Plan

The Second Basic Plan (2001) cited the importance of communication between science and society, but its main focus was mainly on communication between researchers in science and engineering and those in the social sciences and humanities. The public's understanding, assessment, and acceptance of science were mentioned, but the major actors charged with evaluating science and technology were natural scientists, technological experts, and experts in the social sciences and humanities. This second plan cast the reform of science education in the context of international competition, a long-standing motivation for training scientific specialists.

The role of the public in the advancement of science and technology was specified in the fifth chapter of this plan as embracing a responsibility to understand the role of science and technology in daily life, a recognition that science and technology are synergistic activities, and an obligation to develop a level of scientific understanding enabling one to make rational and independent judgments. Interestingly the plan believed that the development of this kind of scientific understanding could occur outside the educational area in institutions like museums.

Yet in spite of the attention paid to public understanding of science, the plan overwhelmingly emphasized the responsibilities of scientists and engineers to act in accordance with ethical standards. Hence bioethics, research accountability, and risk management among scientists and engineers were stressed to a greater degree than the public's responsibility to make rational assessments about science and technology.

68.5.3 The Third Science and Technology Basic Plan

The attitude toward NOS changed drastically in the third basic plan for science and technology (2004). An entire chapter was dedicated to science communication, especially through the proactive participation of the public in scientific and technological issues and the active engagement of scientists and engineers in communicating their work through outreach activities.

The emphasis on science communication in the third basic plan was a reaction to the discussion of issues related to bovine spongiform encephalopathy (BSE) in Japan. Although the Japanese government had discussions on BSE in the United Kingdom since the 1980s, it failed to respond adequately to the threat of the disease. Not until March 2001 did the government act, and by the end of the summer, a BSE-infected cow was found in Japan. An independent investigation in 2002 found the government lax in disseminating information on BSE and preparing the public for the possibility that the disease might be found in Japan. Ill-prepared and confused statements by the government generated public distrust as had also occurred in the UK. As a result the government tried to enact good practices of science communication.

Implementation of the third basic plan for science and technology began in 2005, which Kobayashi (2006) called the first year of science communication in Japan. The following steps were taken to improve the situation:

1. Three universities (Hokkaido University, the University of Tokyo, and Waseda University) introduced science communicator training programs with governmental support.
2. Osaka University launched the Communication Design Center, an interdisciplinary-oriented institute with a strong focus on research, development, and personnel training in science communication.
3. The National Museum of Emerging Science and Innovation began offering a training course for science communicators. It also hired science communicators with a fixed term.
4. The National Science Museum conducted a research project (2005–2008) on training and evaluation of science communicators.
5. Science cafes became common in Japan.

Nevertheless, it turned out that the activities and efforts of science communication had a limited effect in the Japanese society as the whole, with catastrophic results.

68.5.4 The East Japan Earthquake and the Fourth Science and Technology Basic Plan

One of the strongest earthquakes in human history hit eastern Japan at 14:46 on March 11, 2011. The epicenter was 130 km from the Miyagi prefecture coast. The earthquake's magnitude was 9.0, the fourth strongest of recorded earthquakes. It was the first gigantic earthquake where the earthquake waves were almost captured by recorders and subsequent events were broadcast to the world. Within 30 min at the earliest after the earthquake, a tsunami up to 40 m high hit Japan's Pacific coastal areas from Hokkaido to Chiba. About 20,000 people were killed in the tsunami and the earthquake; 118,621 buildings were razed; and 802,814 buildings suffered partial damage. Thousands of people lost their homes and livelihood as a result of the earthquake and tsunami.

The tsunami-affected area included the site of the Fukushima 1 nuclear power plant. Due to loss of electricity, the power plant lost control and four of its six nuclear generators exploded. Radioactive particles dispersed in the air and the Pacific Ocean. Over 113,000 residents in the Fukushima Prefecture evacuated due to high levels of radiation (Cabinet Office 2011). Broadcast in real time over television and the Internet, the earthquake, tsunami, and nuclear accident shocked the world.

The consequences of the Fukushima accident reverberated in the years that followed, and assessments of the damage to society, politics, and the economy were difficult. From an NOS/HPS perspective, the main issue concerned public trust, especially trust in experts. Initially professional opinions on the dangers from Fukushima varied. Some claimed, for instance, that the radioactive level would not immediately affect human body, while others insisted that everybody should evacuate eastern Japan immediately. Due to these contradictions and others like them, the public came to distrust the government, scientists and engineers, and even mass media (and some say, social media too). The public classified some researchers and other professionals as *goyo gakusha* (governmental junk scientists), while it identified others as “sound” professionals. But the public’s criteria for placing someone in one category or another were not clear, indicating a profound inability to assess independently “official” statements about the nature and extent of the crisis. Scientific communication had malfunctioned despite the science communication programs that had been inaugurated in the decade before the accident. Improving public understanding of science and the expert’s ability to communicate science were high priorities in the years following Fukushima.

A complicating factor was the unusual nature of the accident – the probability of a nuclear disaster following an earthquake was thought to be very low – making the crisis one of determining an “unknown unknown.” The environmental and health effects of low levels of radiation were not known, yet decisions had to be made in order to take action on the relocation of the population after the quake. For instance, before beginning the reconstruction of the area, wrecked homes and ships had to be examined for the level of radiation contamination, but it was not clear at what level the radiation was harmful. Reconstruction itself was difficult because debris from the tsunami was left on the roadside more than a year after the earthquake, and roads themselves were often so damaged that they became barriers to the heavy construction vehicles needed to clean up the sites. Finally, the sheer amount of debris exceeded the capacity of plants in the area. Thus, the restoration process needed informed expert *and* public decision-making at the national level.

Furthermore irrational nuclear fears surfaced. Some residents outside the Tohoku area reacted against Tohoku debris, believing that anything in Tohoku was contaminated by radioactive particles. While professional measuring of radiation levels was extensive, the public simply did not believe the data any longer due to the distrust of professionals formed in consequence of miscommunication after the earthquake, the tsunami, and the nuclear reactor accident at Fukushima.

The Fukushima disaster had an added dimension: how to manage the consequences of the tsunami and how to handle reconstruction so that the impact of a future tsunami could be minimized. Thousands of residents lost their homes and had to live in temporary housing. Residents wanted to return to their homes, but whether or not their homes were safe was difficult to determine. Hilly areas are naturally relatively tsunami-proof and it would have been appropriate to move the displaced population to them, but these areas were already built up with little room for expansion. Municipal governments often owned other available plots of land, but they were designated as parks or historical landmarks and therefore could not be occupied by survivors. An added complication was the loss of gainful employment in the area after the tsunami.

Discussions on those issues might have been a little easier if the Japanese public were well educated on NOS and if the public as well as the experts acknowledged that science cannot solve all problems by itself. Tadashi Kobayashi strongly argued for the importance of NOS education for the public in a cabinet meeting in April 2011 in the hope of changing the situation.

The fourth Basic Plan of Science and Technology (2011) was crafted with the problems caused by the earthquake in mind. Greater stress was placed on the role of science communication in social decision-making as well as in the public understanding and awareness of science than had been the case in previous basic plans. The fourth plan explicitly stated that the evaluation of scientists and their work now had to include consideration of the scientist's outreach to the public, including the communication of research results to society.

68.6 Conclusion

The promotion of science and technology in Japan after the Meiji restoration has been motivated by external pressures and global competitions. Engineering was favored over science in education in order to increase innovation through practical results.

NOS in school science (Rika) was the most clearly articulated in the course of study for elementary science revised in 1952 in the early postwar period. The word "science (kagaku)" disappeared from the course of study for elementary science revised in 1977. Shindo (1995) noted that "science," "scientific method," and "scientific inquiry" in Japanese science education should be reconsidered from the point of view of modern science studies. NOS has hardly appeared in any stage of education since it was not included on university entrance examinations, and, with few exceptions, it has been largely excluded from higher education programs in science.

In Japan university courses for science teacher training, even for science majors, usually do not have NOS/HPS-related content. So NOS/HPS is not required to be a science teacher. Toda (1992) investigated the views of science and science teaching methods held by science teachers in training and concluded that teachers in training were never fully conscious of their own specific views regarding science. They tended to hold traditional views of science as common sense, and their choice of science teaching methods was based on "familiarity" and "orthodoxy" rather than informed and up-to-date views of science.

International developments may compel Japanese science teachers to take a different view of their subject and their profession. In 1999 a declaration on science and the use of scientific knowledge was issued under the aegis of the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the International Council for Science (ICSU). The declaration, which addresses scientific knowledge and science education, stated that "Science curricula should include science ethics, as well as training in the history and philosophy of science and its cultural impact" (The World Conference on Science 1999).

In Japan HPS grew in response to nationalist movements and educational reform after WWII. HPS courses since then have been offered mainly for non-science students, with the number of universities offering HPS courses decreasing after successive reforms in higher education. Crisis events such as BSE resulted in an emphasis on improving science communication rather than enhancing instruction in HPS. The earthquake of March 2011 and the subsequent nuclear accidents have drawn attention to NOS/HPS in Japan, but the integration of NOS/HPS courses into the Japanese educational system has been uneven, with most educational sectors ignoring NOS/HPS.

Thus, Japanese society began to realize the importance of NOS in the wake of the East Japan Earthquake and the nuclear accident that followed. There is still a long way to go to change Japanese attitudes in the direction of a deeper understanding of nature and of ways of studying and managing it. NOS and HPS can be of assistance in changing attitudes, but there is much to be done. Concerned parties need to be persistent.

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Chapter 69
The History and Philosophy of Science and Their Relationship to the Teaching of Sciences in Mexico

Ana Barahona, José Antonio Chamizo, Andoni Garritz, and Josip Slisko

69.1 Introduction

Why is science so important in today's societies? Science (along with technology) is one of the salient endeavours of the contemporary world and, more than any other human activity, distinguishes the current period from previous centuries. According to Stehr, it is a widely shared assumption among contemporary social scientists that the immense impact of science and technology on society has become one of its defining characteristics (Stehr 1994).

Nowadays, we are experiencing the fourth, postindustrial, technoscientific revolution, where science and technology play an increasingly important role in most spheres of life and where our dependence on knowledge-based occupations is considerably growing (Böhme 1988). Contemporary society may be described as a knowledge society, based on the penetration of all its spheres by scientific and technological knowledge (Stehr 1994).[1]

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[1] Some authors consider the first of the technoscientific revolutions to be the agricultural revolution; the second, the industrial revolution, (these two revolutions emerged from applying new sources of energy to mass production of goods and the transfer of information theory to industrial processes); the third the informatics and robotics revolution; and the fourth the postindustrial revolution. These revolutions were manifestations of the ever-increasing capacity of human beings to

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Advances in science and technology deeply influence natural and social processes. Science and technology as an instrument of mediation between nature and society have transformed people's lifestyles and their relationship with the cultural and natural environment.

Now we know more about the way the world and the universe work; in matters of health many diseases have been eradicated, and many therapies have been found for others. On the technological side, modern agriculture and industry have been developed to cover the needs of more and more inhabitants of the planet, as well as increasing the possibilities to access information in real time with worldwide coverage. Modern societies cannot function without the products of science and technology; they are now so commonplace that they have become largely invisible.

Changes due to science and technology have generated transformations in the way knowledge is organized and have transformed societies into knowledge societies, where information is manifold, decentralized and available to more and more people around the world. This is why it has become essential to modify the current education system regarding science and technology in countries like Mexico. In order to do so, the inclusion of reflections produced by historical and philosophical studies has been a cornerstone over the last three decades.

The first part of this chapter is about the relationship between the history and philosophy of science and the teaching of science. It will allow us to emphasize the value that recent studies on the history and philosophy of science have had in science education in Mexico. On one hand, in it we stress the importance of the history and philosophy of a discipline in the teaching of science, and on the other, we insist in the role of science in modern societies and encourage science teaching within a historical and philosophical perspective. In the second part we will review the latest Mexican educational reforms in 1993 and 2006 and acknowledge the advances regarding the teaching of biology, physics and chemistry in basic education (elementary and junior high school) as well as the inclusion of the history and philosophy of science.[2]

69.2 The History and Philosophy of Science and Their Relationship to the Teaching of Science

Science, like other human activities, is a complex and social one (Longino 1990). We can say that science is a way of knowing about and explaining the world around us. It differs from other forms of knowledge in its particular ways of observing, thinking, experimenting and testing, which constitute the fundamental aspects of its nature. From a scientific perspective, things and events in the universe

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control and manipulate their environment and resulted in important social and political changes (Hirschhorn 1986; Stehr 1994).

[2] A more broad approach had been boarded by two of the authors (Chamizo and Garritz 2008).

present consistent patterns which can be understood by means of systematic study. Scientists attempt to make sense of the observation of phenomena by formulating explanations based on scientific principles accepted by the community that are compatible with these phenomena.

Science can be understood as a process of knowledge production that not only has instruments which expand the senses and allow careful observations and interventions in phenomena but also establishes the theories which make sense of them (see, e.g. Golinski 1998; Hacking 1983).

Science has a history of elucidating many processes; the way human beings have observed and explained nature has changed through history. At the beginning of the nineteenth century, for example, the existence of genes was unknown, though it was known what happened when one crossed certain plant varieties. Nowadays we have the sequence of the human genome. Change in knowledge is evident and inevitable. Scientists reject the idea that one goal of science is to reach the absolute truth and agree that there is some uncertainty that is part of its nature and modification of knowledge is one of its norms; however, it can be said that most of scientific knowledge is long-lasting. What we know now can be modified or rejected by future observations or theoretical proposals. Therefore, stability and change are integral parts of the nature of science.[3]

Science is not only a collection of data. Concepts, scientific theories and methodologies, along with goals, values, aptitudes and abilities (which are handed down from generation to generation), are an integral part of science. When one teaches or learns science, one does not only teach or learn ‘scientific knowledge’ but also goals and values (objectivity, honesty, collaboration, conservation of nature), abilities (to observe, manipulate, calculate, measure, estimate) and aptitudes (curiosity, openness to new ideas, confrontation of different positions before problems, informed scepticism, communication). Scientific education can and must contribute towards enhancing people’s knowledge as well as to develop scientific values and/or social values in general positive aptitudes and abilities that help improve quality of life. In this sense, schools have an unavoidable social duty, as they are in charge of distributing scientific knowledge to the population.[4]

What is the importance of teaching science? Human beings have everyday principles, which allow them to interact with the world. However, science enables us to have a better quality interaction. In modern societies, active participation and a

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[3] Thanks to recent studies on the history and philosophy of science, it can be said that the different ways in which humanity has explained phenomena, i.e. the different patterns of scientific explanation, have been modified over time (see, e.g. Martínez 1993).

[4] Values have been basic elements of the twentieth-century educational perspective in Mexico, for they have social, political and pedagogical content that expresses the standards of comprehensive human education. For this reason, values have been considered an asset whose conveyance and quality must be promoted. Their presence in the social milieu has been linked to the development of the Mexican educational system since the end of the nineteenth century (Latapí 2003). Nevertheless, as Wuest Silva and collaborators (1997) mention, the study of the role played by the values associated with science and pedagogy did not begin until the 1980s.

sense of critique[5] are essential before the magnitude of the problems we face. For example, in nuclear power, climate change, the loss of biodiversity, atmospheric pollution, serious diseases such as AIDS or cancer, to name a few, scientific knowledge has become valuable in itself, and these issues have caught our attention regarding the relationship between science and society (Shortland and Warwick 1989). The teaching of science and the acquisition of scientific knowledge have value because knowing science allows us to have explanations about natural or social phenomena and develop the capacity to solve problems with efficiency (Matthews 1994/2014).

Over the last three decades, the importance of the history of science in scientific education has been gaining recognition. Below are a few of the most important reasons. The study of the history of science:

- Helps us understand the nature of science as a complex cultural enterprise that can be presented as part of a wider cultural heritage (Jenkins 1989) and therefore helps place professional education appropriately within a broader cultural context. It is not about forming scientists at an early age (which may be a positive effect), but to form informed citizens with the capacity to decide, observe and manipulate their surroundings.
- Gives us a better understanding of the methods and concepts associated with goals and values which are characteristic of different times and that remain stable for long periods.
- Can enable future scientists to improve their response to the challenges posed by the rapid globalization of science and technology (Wilson and Barsky 1998); according to Gooday and collaborators (2008), the history of science has particularly important forms of knowledge and understanding concerning science that cannot be obtained so effectively by any other means, like the ability to read and interpret primary sources and formulate and defend a cogent argument (see also Solomon 1989).
- Allows us to understand how scientific goals and values go beyond disciplinary boundaries and contribute to the reorganization of disciplines and the development of technological advancement, important to the understanding of modern science. For example, the Human Genome Project would have been impossible without the participation of the most important technological firms in charge of making the sequencers, the big philanthropic foundations in charge of financing, the universities and higher learning centres where scientific knowledge is produced and disseminated, etc.
- Allows us to find suppositions which are shared by students and whose critique and abandonment are associated with important scientific advancements. The teaching of the history of science will allow students to locate these presuppositions (or previous ideas) and be in a position to abandon them rationally. For example, a serious

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[5] The role of critical discourse in science is not a peripheral feature, but rather it is at the core of its practice, and without it, it would be impossible to construct reliable knowledge; for authors like Osborne (2010), scientific education must include critical discourse in the teaching of science to foster the ability to reason and argue scientifically.

problem in students at a higher learning level is their lack of post-Lamarckian evolutionary thought. Many explanations of evolutionary processes in these students are those that correspond to Lamarckism which explained, in the nineteenth century, that species were modified due to the needs imposed by the environment: the necks of giraffes were very long because these animals had to continuously stretch them in order to reach the foliage of trees, wisdom teeth do not come out because we do not use them, etc. This kind of Lamarckian thought, where the need creates the organ, is an idea no longer shared by scientists after the theory of evolution by natural selection that Charles Darwin proposed in 1859 in *On the Origin of Species* (see, e.g. Ayala 1977, 1994, 1994b; Ruse 1979, 1996).

- Enables the idea that students put forward their explanations and are in a position to modify them to acquire modern scientific knowledge. In this way, the study of the history of science will help them understand that some of the explanations they provide, though inaccurate, can provoke a conceptual change.
- Constitutes a strong source of suggestions about how the contents and concepts of a course must be organized according to their complexity and can be used to define the pertinent didactic sequences in the development of a topic.
- Finally, allows us to locate scientific and technological developments within the general outlook of the history of humanity, which is useful for understanding the link between a scientific approach and social problems (UNESCO 1999).

One of the authors of this chapter has promoted an initiative to include the history of science in the basic education curriculum of Latin America schools (Chamizo 1994, 2007).

69.3 The 1993 and 2006 Reforms and the Transformation of Science Teaching in Mexico

Mexico has constructed a significant and high-quality scientific and technological system over the last 20 years. However, this system is insufficient before the new challenges imposed by novel problems and international competition. For these reasons, our scientific and technological system must be consolidated and expanded in a very particular way: through the teaching of science and technology in the early stages of individual development. We must emphasize that the development of science and technology in Mexico has public institutions at its foundation. Any project that comes from the State will have as a starting point the cultural, scientific, professional and historical capital generated in said institutions.

Until a few decades ago, basic-level student education regarding science was concentrated on presenting a rigid structure of subjects which tended to promote the idea that science is a great deal of information that, when processed, offers scientifically correct answers about the phenomena in our surroundings. Thanks to the development in historical and philosophical studies of science, it is now thought that the disciplines that make up science were historically formed through posing problems, not the other way around.

69.3.1 The 1993 Reform

During the presidency of Carlos Salinas de Gortari (1988–1994), the Educational Modernization Programme (Programa para la Modernización Educativa) was proposed and enacted in 1993 (known as the 1993 Reform). It contained a diagnosis of the country's situation and proposed a deep structural change. This model implied radical structural changes and the innovation of practices to modify educational content, the ongoing training of teachers, the organization of different educational levels and the integration of basic education in one cycle that would include preschool and basic education (elementary and junior high).[6] All this in order to elevate the quality of education, to reduce backwardness and decentralize the education system.[7,8]

Methodological, conceptual and epistemological aspects were included in the 1993 Reform of the science curriculum and the study programmes for elementary and junior high schools, which meant an advance regarding the conception of modern science in national curricula. The new natural sciences programmes were based on a formative perspective according to the goal of helping students 'to acquire knowledge, capacities, attitudes and values that can be expressed by the development of a responsible relationship with the environment… and to educate children not as scientists in a disciplinary and formal way; instead, students are encouraged to observe, question, and formulate simple explanations about what happens in their surroundings' (Barraza 2001).

Thanks to this reform, there was progress regarding the teaching of science in basic education,[9] for not only elementary and junior high school curricula were modified but also new textbooks[10,11] and new materials were prepared for the

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[6] Elementary or basic education includes compulsory preschool, primary and junior high education. Preschool lasts for 2 years (4–5 years old), primary education lasts for 6 years (6–11 years old) and junior high education lasts for 3 years (12–15 years old).

[7] On March 4, 1993, the Article 3 of the Constitution was amended, assigning a mandatory character to junior high school. This fact provoked one of the most important changes in the 70-year life of junior high school since its foundation. This reform was incorporated into the General Education Act (Ley General de Educación), enacted on July 12, 1993. In this way the government, through the Ministry of Public Education (Secretaría de Educación Pública, SEP), together with the states, committed to the decentralization of education, to 100 % coverage and to raising its quality levels.

[8] The SEP was founded in 1921 by the Mexican government. Since then, this ministry has designed the content of the national curricula for all subjects for basic education.

[9] The teaching of science in elementary school includes biology, physics and chemistry.

[10] In 1959 the SEP launched a new program, the Free-Text Program (Gilbert 1997), which established the National Commission for the Free Textbooks (Comisión Nacional de Libros de Texto Gratuitos, Conaliteg), and the production of the national textbooks for all basic education subjects, which are based on the national curricula. These textbooks, official and distributed for free, are still being handed out to every basic-level student, teacher and school (private and public, urban and rural) in the country, giving access to all basic-level students to education. These textbooks provide specific guidelines for each grade and are considered excellent sources of information.

[11] It is worth mentioning that some science educators were engaged in the production of the elementary textbooks around 1996 and added a good deal of history and philosophy of science to them.

teachers, with a focus that attempted to centre the teaching of science according to the modern ideas of the history and philosophy of science mentioned above.

Bonilla and colleagues (1997a, b) and Chamizo (2005) have documented this reform. The natural sciences' programme for primary school included five major topics: living beings; human body and health; environment and environmental protection; raw material, energy and change; and science, technology and society (STS). The STS dimension of teaching science corresponds to a large need of innovation in science education. As early as 1971 Jim Gallagher proposed a new goal for school science: 'For future citizens in a democratic society, understanding the interrelationships of science, technology and society may be as important as understanding the concepts and process of science' (Gallagher 1971, p. 337).

As is it outlined by Aikenhead (2003) in his synopsis on the origins and dispersion of this new approach of teaching science, the name STS was coined by John Ziman (1980) in a book titled *Teaching and Learning about Science and Society*. In spite of its title, the book consistently referred to STS in its articulation of the rationale, directions and challenges for STS in school science. It is important to mention that Aikenhead mentioned the following sentence about the relationship of history and philosophy of science with the STS scheme: 'A more comprehensive treatment of STS includes the internal social context (the epistemology, sociology and history of science itself) as well as the external social context of science' (2003, p. 63). It must be emphasized that the recent inclusion of STS in Mexican education means recognition of the importance of history and philosophy of science (Garritz 1994).

Peter Fensham (1985), in his famous paper *Science for All*, contributed directly to the evolution of STS by forging links between science education and technology education, embedded in social contexts relevant for all students. Fensham (1995) has mentioned in the Mexican *Chemistry Education Journal* that in 1984 the Science Council of Canada reported on a 4-year study of school science in that country. The title was 'Science for Every Citizen'. A year later the Royal Society in London published a manifesto, 'Science for Everybody', as part of a larger report on the public understanding of science. In 1988, Australia's Curriculum Development Centre put out a national discussion document entitled 'Science for All', and in 1989 the American Association for the Advancement of Science summarized phase 1 of its Project 2061 under the title *Science for All Americans.* Finally, before the Mexican reform, UNESCO and ICASE had launched 'Project 2000+: Scientific and Technological Literacy for All' (ICASE 1993).

In the Mexican reform of junior high school, the diverse methodologies of each one of the sciences (biology, physics and chemistry) were acknowledged, and the curriculum changed from 'natural sciences' to 'biology', 'physics' and 'chemistry'.

69.3.2 Biology: The Teaching of Evolution

For natural sciences in elementary education, it was established that biology (its first three topics: living beings, human body and health, environment and environmental protection), from the third to the sixth grade, should be taught from an evolutionary perspective. Evolution itself became a subject in the sixth grade.[12]

> Diverse themes with an evolutionary focus were introduced in the beginning of the third grade. For example, there is a discussion of plants' capacity to nourish themselves and how this relates to the oxygen that we breathe today, which comes from photosynthesis of plants that existed thousands of years ago […] Throughout the development of themes regarding the study of plants and animals, there are multiple references to the importance of adaptations that are a result of the evolution of the species […] In the fourth grade, the study of evolution is reinforced when, among many examples, students learn about the role of human beings in changing ecosystems. In the fifth grade the subject of "cells, one-cell and multi-celled organisms" is introduced. Fifth-graders also learn about the first grand division between one-celled organisms with a nucleus and one-celled organisms without a nucleus or bacteria. (Barahona and Bonilla 2009, p. 16)

The sixth-grade programme extensively included evolution: the origins of the earth, the transformation of ecosystems (throughout time and due to continental drift), fossils, the extinction of species, geological eras, Darwin and his book *Voyage of the Beagle*, the concepts of natural selection and adaptation, among others. This resulted in a fundamental transformation of the curriculum and textbooks, as previous materials had discussed knowledge about the origin of species in a purely descriptive manner. This change constituted a great challenge for the design and elaboration of the new third-to-sixth-grade Mexican textbooks (Barahona and Bonilla 2009).

As Shortland and Warwick (1989) have shown, historical case studies draw attention to the failures and disappointments that often follow long years of work or to the communal effort that goes into the production of new scientific knowledge. This viewpoint was particularly crucial for the teaching of evolution in elementary and junior high schools. The inclusion in the six-grade programme of Darwin's Voyage of the Beagle is an example of how historical case studies can show not only on evolution and Darwinism but also on the teaching of the nature of science, the scientific method and the role of evidence in science.

In sum, the 1993 curriculum and textbooks were an important leap forward and indeed a great advance over other educational systems that still question the value of including the Darwinian theory in elementary school.[13]

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[12] This was already a requirement in the 1970s but only as a junior high school subject among many. For example, the discussion was limited to the study of fossils as evidence of life in the past, with illustrations that showed the gradual evolution of horses as well as the differences between contemporary humans and their ancestors; the references to Darwin were minimal (Barahona and Bonilla 2009).

[13] According to the 1993 Reform, the federal authorities launched a new curriculum including these new perspectives in 1997 for teacher's colleges; 4 years later, in 2001, the first group of elementary school teachers graduated with this training. However, there has been no evaluation as to whether the training truly is enabling them to teach natural sciences with an evolutionary focus or, even more importantly, if the students manage to develop an evolutionary mindset.

69.3.3 Chemistry and Its Social Benefits

In junior high school there were three courses in which chemistry was involved: in the first year 'introduction to physics and chemistry', in the second 'chemistry I' and in the third 'chemistry II'. A thorough revision of the curriculum changes and the teachers' training effort needed for this reform is detailed in Chamizo, Sánchez and Hernández (2006). The major theme in chemistry I is the identification of the particulate nature of matter until its concretion in Bohr's atomic theory. The third course is centred on energy and environmental topics (Chamizo 1992).

The most important change in the chemistry curriculum of the 1993 Reform surely was the focus on the STS dimension. The main purpose of the two last chemistry courses is quoted as being one where 'pupils preserve the main elements of basic culture, to enrich their vision of Mexico and the world and assess social benefits that represent the contribution of this science, as well as the risk of its inappropriate utilization' (SEP 1993, p. 95).

The six units in which the courses chemistry I and II were divided had the following names:

Unit 1. You and chemistry
Unit 2. Matter: its manifestations. Mixtures: its separation. Compounds and chemical elements
Unit 3. The discontinuous nature of matter
Unit 4. Water, dissolutions and chemical reactions
Unit 5. Burning fuel. Oxidations
Unit 6. Electrochemistry

The necessity to include environmental education topics is emphasized often. The following can be mentioned as examples: acid rain, ozone and low atmosphere contamination; management of industrial residues; sulphur and nitrogen oxides produced by internal combustion machines; chlorofluoroalkanes; and the ozone hole in the stratosphere. And the STS focus insists in integrating the same critical stance on everyday chemical products such as acids like vinegar, lemon juice, gastric juice; bases like antacids or drain cleaner; colloids like gelatin, mousse, mayonnaise or egg white; hydrocarbons like gasoline, candle, gas cooker, asphalt; and gases solubility like soda and fish tanks.

The introduction of historical facts and biographies of scientists is welcome, because 'science is not a mystery, but a product of human activity…It is not about fulfilling an encyclopaedic commitment, but about giving science a vitality focus' (Chamizo and Garritz 1993, pp. 136–7).[14] A relevant point of this reform is that an ambitious updated programme accompanied it for teachers, which included readings from various issues of history and philosophy of chemistry and physics (Chamizo et al. 2006). An interesting impact of the 1993 Reform in chemistry was documented by applying a 'chemistrymeter' to a set of students just finishing its secondary studies (Tirado et al. 2001).

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[14] A couple of more references on the philosophical bases of this reform can be found in Chamizo (1994, 2001).

69.3.4 School Physics and Philosophy of Science

Like chemistry, physics had its curricular presence in three junior high school years: introduction to physics and chemistry, physics I and physics II, taught in the first, second and third grades, respectively. Some aspects of modern philosophy of science are clearly presented among general aims of the subject, such as:

1. The students should think about the nature of scientific knowledge and how it is generated, developed and applied (SEP 1993, p. 77).
2. Formulations of an alleged scientific method, unique and invariable and formed of successive phases should be avoided in teaching. That version of the method is hardly adequate for the students and does not correspond to the real steps which scientists follow in carrying out their work. It is more valuable that students have a vision according to which scientific knowledge production from systematic and rigorous procedures and from intellectual flexibility derive in a capacity to plan adequate questions and search for unconventional explanations (SEP 1993, p. 78).
3. Physics should be presented as a product of human activity and not as an accidental result of work of a few exceptional persons. To this aim, it is convenient to propose examples of scientific developments motivated by challenges and problems which appear in social life and to stress concrete cases in which scientific advances are results of the accumulative work of many people, although they may have worked independently and in different places (SEP 1993, p. 78).

The inclusion of physics' history is rightly suggested as a way to exemplify the nature of science: 'It is convenient to study and discuss biographies of important persons in physics history, not as an encyclopedic recount, but stressing the forms of reasoning, inquiry, experimentation and error correction which leaded to some relevant discoveries and inventions' (SEP 1993, p. 78).

Although the importance of philosophy and history of science is clearly stressed among the general aims of the physics' curriculum, it is not explicitly materialized and specified at the content level. Only three obligatory topics have this historical and philosophical perspective:

Physical view of the world
Analysis of the Galileo Galilei's experiments and their relevance in scientific work
The ideas of Copernicus, Galileo, Kepler, Newton and Einstein

Without clear curricular indications about philosophical and historical themes, further developments of the intended curriculum were left to the textbook authors. Common models of curricular processes in science education fall into three levels (Robitaille et al. 1993; Valverde et al. 2002):

1. Intended curriculum (aims and goals)
2. Potentially implemented curriculum (textbooks and other organized resource materials) and factually implemented curriculum (teachers' classroom strategies, practice and activities)
3. Attained curriculum (students' knowledge, ideas, constructs and schemes)

At the level of the potentially implemented curriculum and in the absence of further guidelines, historical themes can have very distinct and arbitrary presentations. This was the case in 15 authorized physics' textbooks, written according to the 1993 curriculum reform, where three famous experiments by Galileo had diverse presentations. Regarding the Pisa Tower experiment, five authors did not mention it, five authors described it in a relatively acceptable way and five authors treated it completely wrong. Namely, these last authors present it as an experiment in which times and positions of a body in free fall were measured exactly. Obviously, the authors ignored that such measurements were technologically impossible in Galileo's time. Precisely due to this impossibility, Galileo designed and carried out his groundbreaking inclined plane experiment!

Eleven authors did not mention the thought experiment, one author treated it properly by using Galileo's account of it and three authors presented it as a real experiment.

The inclined plane experiment also had diverse presentations in physics' textbooks. Five authors omitted to mention it; only two authors gave it a satisfactory treatment, while eight authors presented that historically important experiment either wrongly or incompletely.

As all authorized textbooks passed an expert evaluation by the Mexican Ministry of Public Education, the authors are not the only ones to blame. It means that real content and meaning of historical episodes should be disseminated among textbook authors and reviewers (maybe via workshops organized by educational authorities), especially when such episodes form part of the intended national curriculum's objective in order to give students a reliable information about how science works. Furthermore, for an adequate curricular impact in Mexican classrooms, a pedagogical analysis and implementation strategies of such historical episodes should be included in professional programmes for in-service and prospective teachers.

69.3.5 The 2006 Reform

During the presidency of Vicente Fox Quesada (2000–2006), the Junior High School Reform (Reforma de la Escuela Secundaria, RES) was undertaken by the federal government in the National Programme of Education (Programa Nacional de Educación) 2001–2006. It established that the 'Mexican State must offer democratic, national, intercultural, secular and mandatory education that favours the development of the individual and his community, as well as a sense of belonging to a multicultural and multilingual nation, and the awareness of international solidarity of the educated' (SEP 2006).

In 2000, Mexico dedicated 100 dollars to each one of its elementary students. This amount that can be compared with the 600 dollars spent in the USA, the 130 USD used for Argentineans and the 220 USD spent by Chileans (Chamizo et al. 2006).

The designing group of this reform spent a lot of sessions deciding the order in which the three natural sciences should be presented. The decision was centred in a

Table 69.1 2006 Reform. Secondary science contents

Sciences I (emphasis in biology)
Unit I. Biodiversity: result of evolution
Unit II. Nutrition as the base for health and life
Unit III: Respiration and its relation with the environment and health
Unit IV. Reproduction and the continuity of life
Unit V. Health, environment and quality of life
Sciences II (emphasis in physics)
Unit I. The description of movement and force
Unit II. Laws of motion
Unit III: A model to describe the structure of matter
Unit IV. Internal structure of matter manifestations
Unit V. Knowledge, science and technology
Sciences III (emphasis in chemistry)
Unit I. The characteristics of materials
Unit II. Properties of materials and their chemical classification
Unit III: Materials transformation: chemical reaction
Unit IV. Formation of new materials
Unit V. Chemistry and technology

Project 2061 document (AAAS 2001) that recommended biology first, physics second and chemistry third. The natural sciences programmes were called sciences I, II and III, in accordance with the three grades in junior high school. In the first grade the students take sciences I (biology), in the second sciences II (physics) and in the third sciences III (chemistry). The scientific contents of the 3 years of education are represented by the titles of its units in Table 69.1.

At the end of each unit or at the end of the course, projects are developed by each student or groups of students as a good way to develop competencies because ‘it favors integration and application of knowledge, skills and attitudes, giving the study a social and personal meaning’ (SEP 2006).

Often, the projects select aspects related with the everyday life of students and their interests. Projects must favour attitudes as curiosity, creativity, innovation, informed scepticism and tolerance towards different ways of seeing the world. Each project requires the consideration of historical aspects as well as experimental work, and at the end students have to share their results. This objective was based on Stone and Tripp (1981), SATIS (1986) and Chamizo and Garritz (1993).

Some studies made a diagnosis of the scientific curriculum in basic education in Mexico prior to the 2006 Reform. For example, among the problems detected in the teaching of science, Flores and Barahona (2003) found a split between elementary and junior high schools; problems associated with the conception, development and decoupling of science and technology; the inadequate incorporation of the history of science in some subjects; little exploration of values and, finally, that science had not been inserted into the frame of culture.

It is necessary to emphasize that the teaching of science and technology was not marginalized, but played an important role in the focus of the curricula and new textbooks. This reform, despite requiring improvement in the future regarding the teaching of science and technology, promises to be a necessary step for the consolidation of a national science and technology programme and establishes graduation profiles related to science. Some of the most sensible decisions are mentioned below:

> The history of science employs a line of argument and reasoning to analyse situations, identify problems, formulate questions, pass judgment and propose diverse solutions. The teaching of science selects, analyses, evaluates and shares information from diverse sources and takes advantage of technological resources within reach to deepen and widen the learning of science in a permanent manner. It employs knowledge acquired with the purpose of interpreting and explaining social, economic, cultural and natural processes, as well as to make decisions and act, individually or collectively, to promote health and care for the environment as ways to improve the quality of life. (SEP 2006)

Also, the RES mentions the need to take advantage of information and communication technologies in general education, and particularly in scientific education, for this is a powerful tool in the socialization of knowledge and holds important pedagogical and didactic possibilities. The RES starts with a broader vision of technological education, understood as a social, cultural and historical process, which allows students to develop knowledge to solve problematic situations in an organized, responsible and informed manner, as well as to meet needs of a diverse nature. Technological education must contribute to the training of students as competent and critical users of the new technologies, in order to face the challenges of today’s society.

It was established in this reform that scientific training is a goal for boosting cognitive development, strengthening individual and social values in teenagers as well as learning to reflect, exercising curiosity and using informed critique and scepticism, which will allow them to decide and, when necessary, act. A fundamental epistemological focus of the teaching of science relates to the understanding of science and technology as historical and socially constituted activities performed by men and women from different cultures.

The way in which different cultures in Mexico explain and construct knowledge about nature constitutes a practice that arrives nowadays through knowhow, folk knowledge and techniques in which different logics for building knowledge are mixed. From there, it is important to know, recognize and value such perspectives (SEP 2006). The history of science, according to this point of view, gained particular importance in the modification of the study programmes.

The RES expects that when students finish junior high school:

1. They have broadened their conception of science, of its processes and interactions with other areas of knowledge, as well as its social and environmental impact, and value in a critical manner their contributions for the betterment of the quality of life of people and the development of society.

2. They have advanced in the understanding of explanations and arguments of science about nature and use them to better understand the natural phenomena of their surroundings, as well as to place themselves within the scientific and technological development context of their time. This implies that students build, enrich or modify their first explanations and concepts, as well as develop abilities and aptitudes that provide them with elements to configure an interdisciplinary and integrated vision of scientific knowledge.
3. They can identify the characteristics and analyse the processes that separate living beings, relating them to their personal, family and social experience, to know more about themselves, their potential, their place among living beings and their responsibility in the way they interact with their surroundings, so they can participate in promoting health and the sustainable conservation of the environment.
4. They progressively develop knowledge that favours the understanding of concepts, processes, principles and the explanatory logic of science and its application to diverse common phenomena. They should go deeper into basic scientific ideas and concepts and establish relationships among them so they can build coherent explanations based on logical reasoning, symbolic language and graphic representations.
5. They have boosted their capacity to handle information, communication and social coexistence. This implies learning to value diverse ways of thinking, discern between founded arguments and false ideas and make responsible and informed decisions, at the same time as strengthening self-confidence and respect for themselves and for others (SEP 2006).

69.3.6 Biology: The Essence of Evolution

In the case of biology, evolution and genetics appear as central pillars in its teaching. For this reason the teaching of biology in junior high school starts with integrative theories such as evolution by natural selection, referring to biology as a scientific discipline from a historical perspective. Many references to Darwin's construction of the theory are taught in order to focus the attention of students on the historical and epistemological aspects of this discipline. Following the elementary school curriculum, the teaching of evolution is reinforced in junior high school. Regarding genetics, Mendel's laws are taught using his famous experiments with peas to show the manifold aspects of the experimental method in biology.

According to the RES in junior high school, as in elementary school, the scientific learning method must be encouraged, not as the scrupulous monitoring of a series of steps to be followed mechanically (observation, hypothesis, experimentation), but as a flexible and applicable method for the construction of knowledge over a whole course, not only in biology but also in other subjects such as physics, chemistry and geography.

In the 1993 Reform, the changes to the content of the educational programmes represented progress considering the epistemological and pedagogical references, but social aspects remained much diluted. For this reason the intercultural perspective was included in the RES, based on the idea that the diversity of forms in which human beings build knowledge about nature is of a cultural, social and historical order. In our country, cultural diversity has been the source of multiple ideas, explanations and interpretations, which have enriched, complemented and sometimes strained the development of scientific and technological knowledge. It is very important to recognize the diversity of ways to interpret the world and how, in some cases, these have aided scientific developments (like herbalism), or native technological development, which is beneficial to communities' relationship with the environment (SEP 2006).

69.3.7 School Physics and Philosophy of Science

In general terms, the 2006 curriculum framework is much better articulated than the 1993 version to move school physics activities closer to authentic science practices (Chinn and Malhortam 2002). Namely, it is planned that students gain basic scientific culture, in resonance with actual constructivist views on school science learning, through various (and even ambitious) learning tasks:

(a) Select and relate, in a causal and functional way, adequate variables to explain phenomena.
(b) Establish relationships between fundamental concepts which make it possible to construct coherent interpretative schemes in which logical reasoning, symbolic language and graphical representations are involved.
(c) Pose questions, elaborate hypothesis and inferences and construct explanations of some ordinary physical phenomena.
(d) Carry out experiments, get information from diverse sources, use different means to make measurements, analyse data and look for alternative solutions.
(e) Communicate, listen to and discuss ideas, arguments, inferences and conclusions related to physical concepts and their applications in scientific, technological and social contexts (SEP 2006, pp. 65–66).

Explicit curricular spaces and times for such activities are dedicated to develop projects which students are supposed to carry out at the end of each of five blocks.

As in the 1993 curriculum, philosophical aspects of science are not among explicit general aims. Nonetheless, the historical development of physics, the nature of scientific knowledge construction, the integration of science and relationships between science, technology and society are supposed to be taken into account, together with different students' comprehension levels, conceptual problems and previous ideas, as criterions for selection, organization and continuity of the course content (SEP 2006, p. 66)

Such intention is clearly visible in the general structure of the physics course parts, summarized in the Table 69.2.

At the content level, historical and philosophical aspects of physics have a more visible presence than in the 1993 curriculum. Besides the Galileo's

Table 69.2 Relationships between physics domains, representational means and thematic blocks

Physics domain	Elements for representations of physical phenomena	Thematic blocks
Study of motion	Descriptive schemes	Block I. Description of the changes in nature
Analysis of forces and changes	Relationships and sense of mechanism	Block II. The forces. Explanations of the changes
Particulate model	Images and abstract models	Block III. Interactions of matter. A model for description of unseen
Atomic constitution	Images and abstract models	Block IV. Manifestations of internal structure of matter
Universe, interaction of physics, technology and society	Integrated interpretations and relationships with environment	Block V. Knowledge, society and technology

contribution to science (SEP 2006, p. 76), students are supposed to know not only about motion laws but also about the role Newton had in the development of scientific thinking (SEP 2006, p. 86). In addition, the historical development of kinetic model and the atomic model of matter (SEP 2006, p. 102) are mandatory contents.

However, the main difference regarding the 1993 curriculum is the central place given to scientific models. Students are supposed to learn about the general role of models in the construction and verification of scientific knowledge. This intention is explicitly stated in the subthemes (what is the use of models, the models and the ideas they represent, the role of models in science) and curricular goals (the role of models in explanations of physical phenomena, as well as their advantages and limitations).

Nevertheless, the features of scientific models presented might be misleading for the expected learning results. It is said that students should 'recognize that a model is an imaginary and arbitrary representation of objects and processes which include rules of its function and is not the reality itself' (SEP 2006, p. 94). Strictly speaking, although theoretical models in physics are abstract representations and not copies of reality, they are not arbitrary because their predictions must be in concordance with observations.

Regarding textbook presentations of Galileo's work, the situation is similar as it was with the 1993 curriculum. Majority of authors treat the inclined experiment either inadequately or wrongly (Miguel Garzón and Slisko 2010).

69.3.8 Chemistry Presented as Projects and Models

Following the proposal expressed in the course of physics regarding the use of models, an important emphasis on the features of models in scientific explanation is made in chemistry (Gilbert and Boulter 1998, Chamizo 1988). Teachers generally ignore the issue, as exposed in educational research whose products have been books (Chamizo and García 2010) and articles on training experiences (Justi et al. 2011) and the reconceptualization of the subject (Chamizo 2011).

Nevertheless, this reform took into serious account Jensen's proposition of three Chemical Revolutions (1998) and explicitly mentioned them even in the programme (SEP 2006). The types of projects mentioned in the curriculum are scientific, technological and of citizenship. At the end of the units, the following projects must have been developed:

Unit I. The characteristics of materials
Projects related with separation methods to purify substances from mixtures. Or the work developed in a salt installation and its impact to the environment. Discussion, evidence research, information and communications technology (ICT) use, measurement, information analysis, interpretation of results and argumentation are to be fostered.

Unit II. Properties of materials and their chemical classification
The suggested projects point to the identification of elements of the human body, its health and environmental implications.

Unit III: Materials' transformation: chemical reactions
Projects related with soap production, energy release and absorption by human body are suggested.

Unit IV. Formation of new materials
In the framework of sustainability, the projects suggested have to do with avoiding corrosion or with fuel efficiency.

Unit V. Chemistry and technology
These technologic projects are developed to integrate the four previous units. The following topics are suggested: synthesis of an elastic material, Mexican contributions to the chemistry of fertilizers and pesticides, cosmetic products, Mesoamerican construction materials, chemistry and art and the importance and impact of petroleum products.

69.3.9 The Recent Years

During the Presidency of Felipe Calderón Hinojosa (2006–2012), the Mexican authorities launched a new reform in 2009 that has not yet concluded. It began in 2009 with curriculum changes to the first and sixth grades, in 2010 the changes affected the second and fifth grades, and finally in 2011 they included all the grades of elementary school. In July 2011, the SEP announced a new junior high school reform that intended to link all basic education levels (preschool, elementary and junior high school) and the production of new textbooks accordingly. Much of the progress made in previous reforms regarding the introduction of history and philosophy of science in science education was lost, particularly in the production of the most recent science textbooks.[15]

This new reform, called the Integral Reform for Basic Education (Reforma Integral de la Educación Básica, RIEB), intended to give continuity to the curricula and study programmes of all basic education. The organization of the subjects remained the same, although big changes were introduced in the natural sciences curricula (SEP 2011).

The national standards for science are the acquisition of scientific literacy, the use of scientific and technological literacy, development of skills associated with science and attitudes towards science. It does not mention the use of the history and philosophy of science in the teaching of sciences, and in the case of sciences I (biology), many topics about evolution are missing, but most importantly biology is not taught from an evolutionary perspective. The references to Darwin are very few, the Voyage of the Beagle is not mentioned, and fossils are seen as evidence of living beings in the past (not as relatives of present organisms). Although the topic of biodiversity is seen as the result of evolution, little is said about the processes that make up biological diversity and the evolutionary history of organisms. The teaching of biology in this reform is descriptive in comparison with the two previous ones.

69.4 Conclusion

We have tried to illustrate how science and technology are essential and at the same time constitutive parts of the modern society known as the knowledge society. Their importance demands, on one hand, reflection on the impact and scope of knowledge and, on the other, the modification of the educational agenda to make scientific and technological knowledge available to everyone. This strategy goes beyond the introduction of natural sciences as mandatory subjects; it implies a different focus on the selection, organization and sequencing of contents and the way to work with them.

It is decisive to collaborate in the change of the public perception of science and technology. In knowledge societies it is necessary that citizens have a positive attitude towards science and technology. This means that they have scientific and technological literacy that allows them from an early age to understand the potentials, benefits and risks of technoscientific products. This way, citizens, as well as local, municipal or federal officials, can make informed decisions before the problems technological changes produce in society take effect.

In this sense, the educational reforms in Mexico, the 1993 Reform and the RES, manifest the significance that the history and philosophy of science have had in the conception of teaching of science. Particularly, evolution and STS in Mexican education constituted an important advancement. It is worth saying that the

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[15] These two reforms (2009 and 2011) are so recent that it is impossible for us to make an evaluation that provides a comparison with regard to the reforms referred to in this document.

introduction of the history and philosophy of science into the formal science curriculum in Mexico took the country some steps forward and some backward. For instance, the 1993 natural sciences programme for elementary education was more progressive regarding the history and philosophy of science than the 2006 programme for junior high education, and contrary to these advances, the 2009–2011 Reform lacked the teaching of science from a historical perspective and the evolutionary one regarding biology. This is to say that in the latest reform 2009–2011, the history and philosophy of science in relation with the teaching of biology is absent. We must wait for results to modify glitches and consolidate progress.

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Chapter 70
History and Philosophy of Science in Science Education, in Brazil

Roberto de Andrade Martins, Cibelle Celestino Silva,
and Maria Elice Brzezinski Prestes

70.1 Introduction

This paper addresses the context of emergence, development, and current status of the use of history and philosophy of science in science education in Brazil. Its main scope is the application of this approach to teaching physics, chemistry, and biology at the secondary school level.

The first Brazilian researches and projects along this line appeared in the decade of 1970, although before that time it is possible to find scattered claims of the relevance of history and/or philosophy of science in science teaching. From the decade of 1980 onwards, the importance of this approach became widely accepted, and the subject became a common theme of educational dissertations and theses, appearing with a considerable frequency in papers presented at conferences on science education and published in educational journals. Since 1998, the use of history and

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philosophy of science was included among the government recommendations for secondary school science teaching in Brazil. Nowadays, this is an important line of research in graduate programs on science and mathematics education. However, the actual use of this approach in secondary education is still a desideratum.

Before entering in the main subject, this paper will present a short overview of the development of philosophy of science, history of science, and science education in Brazil, especially from 1960 onwards.

70.2 Philosophy of Science

The main development of philosophy of science in Brazil, in the twentieth century, began after the creation of the University of São Paulo (USP) in 1934. From its very inception, this university established a practice of bringing to Brazil foreign researchers to help starting new disciplines and research lines. In the case of philosophy, the main foreign professors were French: Jean Maugüe, from 1935 to 1943; Giles Gaston Granger, from 1947 to 1953; Martial Guéroult, from 1948 to 1950; Claude Lefort, from 1955 to 1959; and Gérard Lebrun, from 1960 to 1966 and from 1973 to 1980 (Hopos 2000). There were other strong influences, too. For instance, in 1942, Willard Van Orman Quine spent a few months in Brazil. However, the main influence was French, and Guéroult's approach to history of philosophy dominated the University of São Paulo for decades (Lefebvre 1990).

During his short stay at the University of São Paulo, Quine learned Portuguese and wrote in this language his book *O Sentido da Nova Lógica* (*The Meaning of the New Logic*), published in Brazil in 1944 (Quine 1944; Stein 2004, p. 376).[1] However, Granger was the main reference for philosophy of science at USP, for a long time. His first book was published in Brazil, in Portuguese, in 1955: *Lógica e Filosofia das Ciências* (*Logic and Philosophy of Science*) (Granger 1955).

Notwithstanding those precedents, philosophy of science would only begin to bloom in Brazil in the 1970s (Salmerón 1991). At the University of São Paulo, the main Brazilian professors who began to develop this line of research were Oswaldo Porchat Pereira da Silva and João Paulo Monteiro. Monteiro, a specialist in Hume (Monteiro 1967), was a strong influence in the development of philosophy of science at USP, attracting new philosophers to this field and creating in 1979 the journal *Ciência e Filosofia* (*Science and Philosophy*).

Oswaldo Porchat, who had studied with Victor Goldschmidt in France, wrote a Ph.D. thesis on Aristotle, but obtained a broad acquaintance with philosophy of

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[1] Quine stayed in 1942 at the *Escola Livre de Sociologia e Política* (*Free School of Sociology and Politics*), which at the time was an "autonomous complementary institution" of the University of São Paulo. At that time, one of the few Brazilian scholars who could interact with him on equal grounds was the philosopher of logic Vicente Ferreira da Silva, who published an important book on logic in Brazil, *Elementos de Lógica Matemática* (*Elements of Mathematical Logic*) (Silva 1940), and later became a Heideggerian.

science (Silva 1967). Although his first connection was with French history of philosophy, he also had a postdoctoral stage at the University of California, Berkeley (1969–1970). In 1975 Porchat left the University of São Paulo to found the Philosophy Department at the State University of Campinas (Unicamp) and the Center for Logic and Philosophy of Science (CLE) at the same university. This center was a main influence in the development of philosophy of science, in Brazil, organizing meetings and publishing two journals: *Manuscrito* (*Manuscript*), since 1977, and *Cadernos de História e Filosofia da Ciência* (*History and Philosophy of Science Notepads*) since 1980. The Philosophy Department at Unicamp started the first Brazilian graduate program on logic and philosophy of science.

Leônidas Hegenberg, after graduating in mathematics, physics, and philosophy in Brazil, spent two years working with Alfred Tarski at the University of California (1960–1962). Returning to Brazil, he completed his Ph.D. in philosophy at the University of São Paulo, in 1968 (Hegenberg 1968). During most of his professional life, he taught mathematics, logic, and philosophy of science at the Technological Institute of Aeronautics (ITA). For that reason, he never supervised any M.Sc. or Ph.D. student. However, he published many papers and books and was highly influential in Brazil. Besides that, he kept up to date with the development of philosophy of science abroad and translated about 60 books to Portuguese, including works by Karl Popper, Paul Feyerabend, Max Weber, Wesley Salmon, Mario Bunge, Derek J. de Solla Price, Charles S. Peirce, and others.

In Rio de Janeiro, a strong tradition in philosophy of science began with the arrival of the Brazilian researchers Raul Ferreira Landim Filho and Oswaldo Chateaubriand Filho, in the 1970s. Chateaubriand obtained his Ph.D. in 1971, at the University of California, Berkeley, on ontology and semantics (Chateaubriand Filho 1971). After teaching at Cornell University from 1972 to 1977, he returned to Brazil, where he finally settled at the Catholic University of Rio de Janeiro (PUC-RJ). Landim, who obtained his Ph.D. at Louvain (Landim Filho 1974), also arrived to Rio at about the same time and was influential in the development of philosophy of science at the Federal University of Rio de Janeiro (UFRJ). Another important philosopher of science, Alberto Oscar Cupani, born in Argentina, obtained his Ph.D. at Córdoba in 1974, moving to Brazil in 1977 (Cupani 1974). He first worked at the Federal University of Santa Maria (UFSM) and then settled at the Federal University of Santa Catarina (UFSC).

Around 1980 the area of philosophy of science was well established in Brazil and had attained an international standard of research. There are currently 12 graduate programs in philosophy of science, several journals, and regular meetings over the country.

70.3 History of Science

History of science, in Brazil, developed later than philosophy of science. Up to 1970 there were few universities with regular courses on history of science (in general) or history of specific scientific disciplines. Those who taught history of science had no specific training in this discipline; they were commonly senior scientists who had a broad cultural background, such as Mario Schemberg and Francisco Magalhães Gomes (physics), Antonio Brito da Cunha (biology), Leopoldo Nachbin (mathematics), and Simão Mathias (chemistry).[2] Up to the 1970s, works on history of science written by Brazilian authors were, in general, descriptive and laudatory accounts of Brazilian researchers and institutions. One of the best productions of this period was a book organized by Fernando de Azevedo, *As ciências no Brasil* (*Sciences in Brazil*), published in 1956.[3]

Research on the history of Brazilian science gradually improved. In 1971 the graduate program of the History Department of the University of São Paulo (USP) established the first research line on history of science. The main focus was the study of Brazilian science, although the group has also produced research and supervised dissertations and theses on the conceptual history of international science. In 1979–1981 they published the three-volume work *História das Ciências no Brasil* (*History of Sciences in Brazil*), organized by Mário Guimarães Ferri and Shozo Motoyama (Ferri and Motoyama 1979–1981).

One stimulus to the study of history of Brazilian science was the expectation that it could help to develop scientific policies. In Rio de Janeiro, the sociologist Simon Schwartzman, who had obtained his Ph.D. in political science at the University of California, Berkeley (Schwartzman 1973), developed an ambitious project to study the Brazilian scientific community. He conducted a large series of interviews with leading Brazilian scientists and in 1979 published the analysis of this work in an influential book: *Formação da Comunidade Científica no Brasil* (*The Development of the Scientific Community in Brazil*) (Schwartzman 2007).

In 1982 the *Sociedad Latinoamericana de Historia de las Ciencias y la Tecnología* (SLHCT) (*Latin American Society of History of Science and Technology*) was founded in México, with the participation of Brazilian historians of science. In the next year, the group of the University of São Paulo created the *Sociedade Brasileira de História da Ciência* (SBHC) (*Brazilian Society of History of Science*) (Motoyama 1988; Bassalo 1992). This association soon began to organize biennial meetings (beginning in 1986) and in 1985 started the publication of the first Brazilian journal devoted to the history of science.

The largest research institution in history of science, in Brazil, is devoted to the study of Brazilian medicine and related subjects: *Casa de Oswaldo Cruz*, in Rio de Janeiro (founded in 1986). Another important institution is the *Museu de Astronomia e Ciências Afins*, MAST (*Museum of Astronomy and Related Sciences*), founded in the same year.

Historical researches on Brazilian science had no impact in science teaching, because the curriculum of the scientific disciplines does not include any topic related to the development of national science.

The Brazilian researches on the history of international science followed another line of development that is more difficult to track down. Diverging from the

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[2] See, for instance, Mathias (1975), Gomes (1978), Nachbin (1996), and Schemberg (1984).

[3] See, for instance, Beltran (1984), Goldfarb (1994), and Vergara (2004).

situation that occurred in philosophy of science, the main stimulus was not the contact with foreign researchers. However, there have been some influential foreign scholars, such as Michel Paty, who spent several periods at the University of São Paulo and also supervised Brazilian students in France.

Around 1980, several scattered scholars who taught history of mathematics, physics, chemistry, and biology began to devote a larger effort to the study of history of science. At this time, there were no graduate courses in Brazil where one could obtain the adequate training for research in the history of international science. Although they had no specific training in this field, they began to produce better research by employing primary sources and to stimulate younger scientists to dedicate themselves to this field. Among other researchers of this generation, we can cite Ubiratan D'Ambrosio and Guilherme de La Penha (mathematics), Aécio Pereira Chagas and Carlos Alberto Lombardi Filgueiras (chemistry), and Roberto de Andrade Martins and Penha Maria Cardozo Dias (physics).[4] Two philosophers who began to devote themselves to the history of science in this period should also be mentioned: Pablo Mariconda and Carlos Arthur Ribeiro do Nascimento (Mariconda 2003; Nascimento 1995).

In 1985, a series of annual meetings on history of science was started at the State University of Campinas, and in 1990 a first attempt was made to establish a graduate program on history of science at the same university. However, internal problems suspended this development. Although dissertations and theses on history of science had been produced at several Brazilian institutions, since the decade of 1980, the first specific graduate course on history of science was created at the Catholic University of São Paulo (PUC-SP) in 1997, the second at the Federal University of Bahia (UFBA) in 2000 (with strong emphasis in science teaching), and the third one at the Federal University of Rio de Janeiro (UFRJ) in 2002. There is also a graduate program on the history of medicine, at Casa de Oswaldo Cruz, Rio de Janeiro, founded in 2001.

From the late 1980s onwards, the number of researchers in conceptual history of science who had received specific training gradually increased in Brazil. Among them, we may cite Olival Freire Jr. and Antonio Augusto Passos Videira (physics); Anna Carolina Regner, Lilian Al-Chueyr Pereira Martins, Gustavo Caponi, and Nelio Bizzo (biology); Ana Maria Alfonso-Goldfarb (chemistry); and Sérgio Nobre (mathematics).[5] Most of them received part of their training abroad. In the decade of 1990, research in history of conceptual science attained an international level, in Brazil.[6]

The strong development of the history of mathematics led to the creation of the *Sociedade Brasileira de História da Matemática* (SBHMat) (*Brazilian Society for the History of Mathematics*) in 1999. This society has its own journal and regular

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[4] See, for instance, Chagas (2001), D'Ambrosio (1996, 2008), Dias (1994, 1999), Filgueiras (1994, 2002), La Penha (1982), La Penha et al. (1986), and Martins (1996, 1997).

[5] See, for instance, Alfonso-Goldfarb (1999), Bizzo (1991, 2004, 2009), Caponi (2010, 2011), Freire Jr. (1995, 2002), Martins (2005, 2007), Nobre (2001), Regner (1995, 2003), and Videira (1994).

[6] For more recent developments, see Krause and Videira (2011).

biennial meetings. In 2000 the *Associação de Filosofia e História da Ciência do Cone Sul* (AFHIC) (*South Cone Association for Philosophy and History of Science*) was created, bringing together scholars from Brazil, Argentina, Chile, and Uruguay. This society gave a new impetus to interchanges between historians and philosophers and stimulated the formation of thematic groups. The idea of creating AFHIC was initially discussed at the *First Meeting of Philosophy and History of Science of the South Cone*, which took place in 1998 at the Federal University of Rio Grande do Sul (UFRGS), Brazil, under the aegis of the Research Group on Philosophy and History of Science (GIFHC), from that university.

The development of research in history and philosophy of biology started with the first *Meeting of Philosophy and History of Biology* that occurred in 2003, in São Paulo, followed by a series of annual conferences. During the fourth meeting, in 2006, the *Associação Brasileira de Filosofia e História da Biologia* (ABFHiB) (*Brazilian Association for Philosophy and History of Biology*) was founded and in the same year began the publication of the journal *Filosofia e História da Biologia*. It is possible to notice a conspicuous interest on the use of history and philosophy of science in biology teaching in the meetings and publications of this society.

Although history of physics is a very strong research area in Brazil, no specific society for its study has been created, neither for the history of chemistry.

The largest part of the researches in history and philosophy of science developed in Brazil had no impact in science education. High-level researches in those fields, written in specialized jargon, published in professional journals or in foreign languages, are seldom read by Brazilian science educators. Besides that, philosophers and historians of science hardly ever write textbooks or popular works in this country.

70.4 Science Education in Brazil

This section will present an overview of the development of science education in Brazil, in the second half of the twentieth century. Although science education can be understood as including all levels from elementary school to graduate studies, the focus here will be the Brazilian equivalent to high school or secondary education, that is, the 3 last years of basic education, preceding higher education. We may confine our analysis to this level, since most researches on the use of history and philosophy of science in science teaching, in Brazil, deal with secondary education.

Before describing the historic qualitative changes in science education in Brazil, it is relevant to remark that in this country only a very small part of the population was able to attain secondary education in the first half of the twentieth century and that this proportion has been increasing up to the present. Around 1995, the Brazilian gross secondary school enrolment ratio reached about 50 %, being much worse than that of other South American countries, such as Argentina (76 %), Chile (73 %), and Uruguay (81 %) (Rigotto and Souza 2005). This unpleasant situation was one of the reasons for the educational reform announced by the Brazilian government in 1996, which proposed several policies for improving the enrolment ratio of students between 15 and 17 years old at secondary schools. The huge quantitative increase of the secondary school enrolment was achieved with a significant deterioration of material conditions and teaching and learning quality. Improving the overall quality of education is the current challenge for educational authorities in the country. Nevertheless, let us go back and review the development of science teaching in that country.

Until the Second World War, the main educational influence in Brazil was European (especially French). Textbooks were translated, laboratory equipment used in demonstrations was imported, and educational methods were copied. Secondary education was not compulsory and there were few public schools offering this level. In general, only people who intended pursuing higher education would enroll in high school. Access to the universities requires both the completion of secondary education and approval in competitive entrance examinations.

Shortly after the end of the war, several changes occurred. The American influence expanded very fast; there was a stronger concern with the scientific development of the country; and there arose the first attempts to develop national teaching projects. The prevalent view was that scientific development was a necessity for industrial and economical development of the country; and the government of President Getúlio Vargas was deeply concerned with those issues.

Two important institutions were created in 1951: the *National Research Council* (CNPq), to stimulate and support scientific researches, and the *Campaign for the Improvement of Personnel for Higher Education* (CAPES), belonging to the *Ministry of Education and Culture* (MEC), with the aim of improving the level of university professors by the creation of graduate courses and international exchange.[7]

In the early 1950s, under the leadership of Isaías Raw, the recently founded *Brazilian Institute of Education, Science and Culture* (IBECC) produced the first laboratory kits developed in this country. This was a nice innovation in education in Brazil, because it introduced low-cost equipment that could be used by students (not for class demonstrations, as the former imported equipments) and had a strong positive influence in science teaching. In the late 1960s, the industrial dimensions of the production of laboratory equipment led to the creation of the *Fundação Brasileira para o Desenvolvimento de Ensino de Ciências* (FUNBEC) (*Brazilian Foundation for the Development of Science Teaching*) to cope with the large-scale production of teaching materials (Villani et al. 2009; Nardi 2005).

In 1965, six centers of science for teaching training and development of educational materials were created in Brazil: in Pernambuco (CESINE), Rio Grande do Sul (CECIRS), Minas Gerais (CECIMIG), Rio de Janeiro (CECIGUA), São Paulo (CESISP), and Bahia (CECIBA). The leaders of those centers were trained at IBECC, in 1966 (Nardi 2005). Most of these initiatives, however, were not maintained to the present day.

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[7] The names of these institutions were later changed to *National Council for Scientific and Technological Development* and *Coordination of Improvement of Personnel of Higher Education*, respectively, although their acronyms were maintained.

Nowadays many critics point out that the empiricist view behind those projects was naïve and inadequate – and that is a correct appraisal (Villani et al. 2009; Nardi 2005). However, positive features cannot be denied. Brazilian science educators had been deeply influenced by John Dewey's work, especially his book *How We Think* (1910). This book was first translated into Portuguese in 1933 and republished in 1953 and 1959. Following Dewey's ideas, science educators were striving to provide a more active involvement of students with science, attempting to develop their reasoning capacity and critical attitude (Freire Jr. 2002).

Notice that, parallel to any innovatory trends, there was a conservative undercurrent in Brazilian education. Essentially, in the 1960s as now, science and mathematics teaching in secondary schools was grounded upon books written with a very simple aim: to train the students to obtain a good performance at the universities' entrance examinations.[8]

In 1961, an educational reform increased the weight of scientific disciplines in both elementary and secondary education. In 1964 a military *coup d'état* and the beginning of a long dictatorship in Brazil (1964–1985) led to deep changes in the educational system, but the previous impetus to improve science education was maintained. The educational influence of the United States increased, and an agreement established in 1965 between the Brazilian *Ministry of Education and Culture* (MEC) and the *United States Agency for International Development* (USAID) led to introduction of many North American educational materials in Brazil (Nardi 2005).

It is well known that in the late 1950s, due to the Cold War between the United States and the Soviet Union, five outstanding American educational projects were developed to improve the teaching of mathematics, physics, chemistry, and biology at high school level: *Physical Science Study Committee* (PSSC), *Biological Science Curriculum Study* (BSCS), *Chemical Bond Approach* (CBA), *Chemical Education Material Study* (CHEMS), and *School Mathematics Study Group* (SMSG). Those projects were introduced in Brazil in the decade of 1960 and they had a strong impact. The textbooks were translated and the experimental kits were reproduced, with small adaptations, by *Instituto Brasileiro de Educação, Ciência e Cultura* (IBECC) (*Brazilian Institute for Education, Science and Culture*). In the United States, about 200,000 students used the PSSC and CHEMS materials, 600,000 used the BSCS texts, and 1,350,000 students used SMSG books. In Brazil, about 400,000 copies of PSSC volumes were published and a similar number of copies of BSCS (Barra and Lorenz 1986, *apud* Nardi 2005). Other foreign products, such as the Nuffield Foundation project, were also translated and used in Brazil (Krasilchik 1992; Villani et al. 2012).

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[8] Universities are free to create any kind of entrance examination. The most traditional one is called "vestibular" and assesses the student's knowledge on the subjects studied in the secondary school. Except the last decade exams conducted by University of Campinas (UNICAMP), "vestibular" in general has a strong inertia regarding the style and content. In recent years, the performance at *Exame Nacional do Ensino Médio* (ENEM) (*High School National Exam*), designed to assess scientific contents and other competencies as reading and comprehension, has also been used as entrance examinations by over 300 institutions. This is a nonmandatory exam, attended by 5.8 million students in 2012.

In the American projects, the use of the "scientific method" was emphasized, with a strong empiricist bias. Those approaches were typical in science education during the 1960s and were still influential in the 1970s, in Brazil.

The reception of the American projects among secondary school teachers was not altogether positive. They had difficulties in dealing with the new methods and contents (Villani et al. 2009). In January 1970 the *Sociedade Brasileira de Física* (SBF) (*Brazilian Physics Society*) sponsored the *First National Symposium on Physics Teaching*. The PSSC project was much criticized, and the participants of the event reached the conclusion that it was necessary to develop Brazilian projects to elaborate new textbooks and laboratory materials. The first initiatives were already on the move, at the University of São Paulo (USP) under the leadership of Ernest Hamburger and at the Federal University of Rio Grande do Sul (UFRGS), by initiative of Marco Antonio Moreira (Oliveira and Dias 1970). Educators such as Pierre Henri Lucie, who was one of the main supporters of the introduction of PSSC in Brazil, were already looking for alternatives. In 1969 Lucie started the publication of an original line of physics textbooks for secondary schools, with a deeper conceptual discussion, using cartoons: *Física com Martins e eu* (*Physics with Martins and I*) (Lucie 1969).

70.5 Brazilian Research and Projects in Science Education

There were new educational reforms in Brazil in 1968 (higher education) and 1971 (elementary school and secondary education). In 1972 the *Ministry of Education and Culture* (MEC) started the *Project of Expansion and Improvement of Education* (PREMEN) to promote an enhancement of education with the development of teaching materials for science and mathematics in the country and adapted to the national context, also providing adequate teaching training for the use of those materials. In the early 1970s, stimulated by government guidelines and financial resources, the formation of research groups and the development of science teaching projects started up in Brazil (Barra and Lorenz 1986).

At that time, three physics teaching projects were under way: *Physics Teaching Project* (PEF) at the University of São Paulo (coordinated by Ernst W. Hamburger and Giorgio Moscati), *Self-Instructive Physics* (FAI) by the *Group of Studies in Physics Teaching Technology* (Fuad Daher Saad, Kazuo Watanabe, Paulo Yamamura, and others), and *Brazilian Project for Physics Teaching* (PBEF) at FUNBEC (organized by Rodolpho Caniato, Antonio Teixeira Jr., José Goldenberg). The three projects were student centered, without expositive classes. The first project had a stronger experimental emphasis which generated a difficulty for its application at secondary schools that could not acquire laboratory equipment. In the two other projects, experiments were secondary activities to illustrate knowledge that had already been learned using self-instructive techniques. The FAI project included passages describing the history of physics, written by Shozo Motoyama. Its books sold 490,000 copies, between 1973 and 1976 (Flores et al. 2009).

In the early 1970s, educational projects on chemistry and biology were also developed in Brazil: *The National Project for the Teaching of Chemistry* (1972), developed by the *Northeast Coordination of Science Teaching* (CECINE), and the Project of Biology Applied to Secondary School (1976), an initiative of the *São Paulo State Center for Science Teaching* (CESISP) (Barra and Lorenz 1986, *apud* Nardi 2005). The most relevant educational initiative in mathematics was developed under the guidance of Ubiratan D'Ambrosio at the State University of Campinas (Unicamp): *New Materials for the Teaching of Mathematics*, for the fundamental school level.

In 1972 the *Brazilian Foundation for Science Teaching* (FUNBEC) and the publisher *Abril Cultural* launched a new project called *Os Cientistas* (*The Scientists*): a series of 50 experimental kits for the study of chemistry, biology, and physics, which were sold in newsstands. Each edition contained an experimental kit, instructions for performing the experiments, and the biography of a famous scientist related to the experiment (Newton, Pasteur, Lavoisier, etc.). This initiative was planned by two professors of University of São Paulo, Isaías Raw and Myriam Krasilchik, and was coordinated by the latter. The project was highly successful and sold three million units (a mean of 60,000 copies of each edition). It was later translated into Spanish, English, and Turkish and sold in other countries (Krasilchik 1990). Although the project included material related to the history of science (the biographies), this was circumstantial: the authors of the biographies and of the experimental kits had no interaction,[9] and the emphasis of the project was an empiricist approach to science.

The development of the area of science and mathematics education along the last decades in Brazil can be noticed in the beginning of regular conferences, founding of societies, creation of journals devoted to school teachers and researchers, and establishment of graduate courses.

The first regular series of congresses devoted to physics education, called *Simpósio Nacional de Ensino de Física* (SNEF) (*National Symposium on Physics Teaching*), started in 1970, one decade before the creation of general congresses devoted to science education in general or to the teaching of the other scientific disciplines such as *Encontro Nacional de Ensino de Química*, ENEQ (*National Meeting on Chemistry Teaching*) (1982); *Encontro Perspectivas do Ensino de Biologia*, EPEB (*Meeting on Perspectives of Biology Teaching*) (1984), discontinued; *Encontro de Pesquisadores de Ensino de Física*, EPEF (*Meeting of Researchers of Physics Teaching*) (1986); *Encontro Nacional de Educação Matemática*, ENEM (*National Meeting on Mathematics Teaching*) (1987); *Encontro Nacional de Pesquisa em Ensino de Ciências*, ENPEC (*National Meeting on Research in Science Teaching*) (1997); *Colóquio de História e Tecnologia no Ensino de Matemática*, HTEM (*Conference of Technology and History of Mathematics Teaching*) (2002); and *Encontro Nacional de Ensino de Biologia*, ENEBIO (*National Meeting of*

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[9] Roberto de Andrade Martins, one of the authors of this paper, can safely state that the two sides of the project were widely independent, because of his personal involvement with the project: he was the author of some of the biographies of *Os Cientistas*.

Biology Teaching) (2005). Most of these are biennial meetings. There are also many regional and local relevant conferences. Besides that, for a long time other general scientific and educational conferences have also included sessions on science and mathematics teaching.

Since 1976, when *Boletim Gepem* devoted to mathematics education was created, many other Brazilian journals on general and specific areas of science education appeared along the years, for instance, *Revista de Ensino de Física, Caderno Catarinense de Ensino de Física, Química Nova na Escola, Investigações em Ensino de Ciências, Ciência & Educação, Revista Brasileira de Pesquisa em Educação em Ciências, Revista de Ensino de Biologia,* and *Alexandria: Revista de Educação em Ciência e Tecnologia,* among many others.

Several scientific societies began to sponsor educational activities, and later on, specific associations were created. The *Sociedade Brasileira de Física* (SBF) (*Brazilian Physical Society*) established a Commission for Physics Teaching in 1970. In 1988 the *Sociedade Brasileira de Educação Matemática* (SBEM) (*Brazilian Society of Mathematical Education*) was founded. In 1997 the *Associação Brasileira de Pesquisa em Educação em Ciências* (ABRAPEC) (*Brazilian Association for Research in Science Education*) and the *Associação Brasileira de Ensino de Biologia* (SBEnBio) (*Brazilian Association of Biology Teaching*) were founded. There are no specific societies related to the teaching of chemistry and physics. In both cases, there are teaching divisions belonging to the corresponding national scientific societies.

Although there were educational initiatives in the several disciplines, physics took the leadership in the establishment of a definite enterprise for the improvement of science teaching. In 1967 the graduate program in physics of the Federal University of Rio Grande do Sul (UFRGS) established the area of physics teaching. The first specific graduate course in science teaching was created in Brazil in 1973, at the University of São Paulo (USP), as a joint initiative of the Physics Institute and the Faculty of Education; about 20 years later, the areas of chemistry and biology were also introduced. There was also an attempt to establish the area of physics teaching in the graduate program created at the Catholic University of Rio de Janeiro (PUC-RJ) in 1967, but it did not succeed. In 1975, the first graduate course in mathematical education started at the Catholic University of São Paulo (PUC-SP) and the second one in 1984, at the Rio Claro campus of the São Paulo State University (UNESP). The latter was the first one to offer a Doctor degree, in 1993. Other graduate courses in science education started at the Federal Rural University of Pernambuco (1995), Federal University of Rio de Janeiro (1995), and at the Bauru campus of UNESP (1997) (Moreira 2004). From 1972 to 1995, 572 theses and dissertations had been finished on science and mathematics education, including those that have been produced at other graduate programs. There was a very fast increase of graduate programs on science and mathematics education from 2000 to 2010, reaching a total of 78 programs in the area at the end of 2010 (CAPES 2010).

In 1999 the first Brazilian graduate program devoted to history and philosophy of science and science education was founded in Bahia State: the *Graduate Program* *in Teaching, Philosophy and History of Sciences* (EFHC). It is an interinstitutional program between Federal University of Bahia and State University of Feira de Santana, with master and doctorate courses (Freire Jr. and Tenório 2001).

70.6 History and Philosophy of Science in Science Education

According to Susana de Souza Barros, it is possible to find several uses of history and philosophy of science in different periods, in Brazil. In the decade of 1970, history of physics was regarded as an important component of the teaching training. The transposition of this historical knowledge to physics teaching at the secondary school level was not discussed, however. During the 1980s, the study of concept formation and conceptual change led to the combined use of psychological, epistemological, historical, and sociological approaches. There were researches using classroom experimentation, and the new line of attack was regarded as useful for the training of physics teachers. Nevertheless, it was not directly applied to introduce educational changes at the secondary school level. During the next decade (1990), there was a strong emphasis on the relation of science teaching and the education for citizenship, using the science, technology, and society approach (STS). The idea that science educators should teach not only science but also about science (i.e., the inclusion of a metascientific level) launched a new use for history and philosophy of science in physics teaching (Martins 1990). Towards the end of the last century, the Ministry of Education established new educational guidelines recommending the use of history and philosophy of science at the secondary school level (Barros 2002).

70.6.1 The Beginning: Physics

It was already remarked that physics was the first area where science education research began, in Brazil. Let us see how the use of history and philosophy of science in physics teaching started and was understood in this discipline, in the early period. This occurred at the University of São Paulo (USP), and therefore our focus, here, will be that institution.[10]

History of physics was taught from the very beginning of the establishment of its undergraduate physics course, at USP. One of the most influential early professors who taught this discipline was Mário Schenberg (1914–1990), a Brazilian physicist with strong political interests. He was a member of the Brazilian Communist Party before this political organization was banned from the Brazilian politics, and he was

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[10] The other early group, at the Federal University of Rio Grande do Sul (UFRGS), did not develop this line of research at first, and its leader complained in 1970 that there was no one available at that institution to teach history of physics (Oliveira and Dias 1970, p. 106).

twice elected deputy of the State of São Paulo (1946 and 1962). He was arrested twice for his political involvement. He was highly influential, and his interest for Marxism and history of science was shared by many other physicists.

Several books on history of science with a Marxist outlook were well known in Brazil, around 1970 (Azevedo and Costa Neto 2010). Friedrich Engels' *Dialectics of Nature* had been translated into Portuguese in 1946, with John Burdon Sanderson Haldane's introduction, and it was republished in 1962 and 1964. It was a very popular book among physicists, at USP, in the 1960s and 1970s. John Desmond Bernal's works were also very influential. Bernal's *Science in History* (1954) was translated in México, in 1959, and in Portugal, in 1965. Both translations, as well as the original English version, were familiar to many Brazilian physicists. Boris Hessen's "The Socio-economic Roots of Newton's Principia" was also well known and highly praised. The Marxist play writer Bertolt Brecht's version of Galileo's life was very popular in Brazil, and parallels were drawn between his struggle with the Catholic Church and the scientists' resistance to the Brazilian military government of that period. The play was enacted in São Paulo, in 1968, with the priests using olive dresses – olive being the color used by soldiers, in Brazil. At that time, the study of the relations between science, history, politics, society, etc. was regarded as a means to denounce the alleged neutrality of science, leading the students to have a more critical view of the scientific endeavor, and also critical of the Brazilian political situation of the time. Students were regarded as citizens that should be educated to deal, among other things, with the political and economic forces surrounding them.

This was a very influential trend, in the early development of the use of history (and sociology) of science in science education in Brazil (Villani et al. 2010). Even now, long after Marxism had become outmoded, its inspiration is still present as an undercurrent in the *science, technology, and society* (STS) approach, in Brazil, although the recent generation is not aware of its early history.

Besides this politically motivated interest in the history of science, there was another view about its educational value. In 1970 the *Harvard Project Physics* was being introduced in Brazil, and its strong use of history of science was described by Giorgio Moscati, who emphasized the motivational aspect of the historical and humanistic approach (Oliveira and Dias 1970). There was a widespread belief that mere contact with history of science could enhance the motivation of students and also to improve their learning of scientific concepts.

This was also, seemingly, the opinion of Pierre Lucie, who taught physics at the Catholic University of Rio de Janeiro. As mentioned above, Lucie had been a strong supporter of the PSSC project in Brazil. However, in 1970 he was devoting himself to other educational projects. In that year he delivered a course on the history of mechanics during the first *National Symposium on Physics Teaching* that occurred in São Paulo. He published a book on this subject in 1978, called *Gênese do Método Científico* (*Genesis of Scientific Method*). This work was not an adaptation of history of physics for science teaching; it was just a plain work on history of science, written by an outstanding educator (Lucie 1978). Several papers published in the early volumes of *Revista de Ensino de Física* (*Journal of Physics*

Teaching), such as those authored by José Maria Filardo Bassalo, were also devoted to the presentation of historical information, without any special application to physics teaching.

Although there was a widespread interest in the history of science at the USP group from its very beginning, its effective influence only began to produce noticeable results in the late 1970s. Let us notice some instances of works produced by the group. In 1978 Amélia Império Hamburger produced a study of physics textbooks, including "the concept of physics and science" among the several features that should be analyzed. In the same year, she wrote a historic and philosophical analysis of mechanics and electricity to help circumventing conceptual learning difficulties. In 1979, João Zanetic wrote a work on the role of history of physics in education. Ernest Hamburger and Joaquim Nestor de Morais presented a historical analysis of the concept of electrostatic potential, comparing it with its textbook presentation. Amélia Hamburger proposed a project using historical examples for teaching physical concepts. In 1980 Alberto Villani started a research on the history of the theory of special relativity. In 1981 Amélia Hamburger began the development of a series of didactic booklets, and one of them contained texts on "science, technology, and society." Zanetic and José D. T. Vasconcellos proposed the introduction of the Popper-Kuhn debate in physics teaching (Gama and Hamburger 1987).

From 1979 onwards, the USP group invited several foreign visitors who delivered courses on history and philosophy of physics: Marcelo Cini (in 1979 and 1980), William Shea, in 1979, and Michel Paty, in 1982, (Gama and Hamburger 1987; Robilotta et al. 1981).

In 1981 Alberto Villani published the first paper, in Brazil, that referred to the so-called spontaneous concepts, mentioning the recently published works (1979) of Laurence Viennot and John William Warren on this subject. Viennot was invited to Brazil and delivered a course on this subject at USP, in 1981. In the following years, this became a very strong line of research of the USP group, involving several researchers such as Villani, Jesuina Lopes de Almeida Pacca, Anna Maria Pessoa de Carvalho, and Yassuko Hosoune, together with graduate students. Three M.Sc. dissertations on this subject were finished between 1982 and 1985 (Gama and Hamburger 1987).

Independently of the USP group, Arden Zylbersztajn, who was a professor at the Federal University of Rio Grande do Norte (UFRN) and had strong interest in history and philosophy of science, started in 1979 his doctoral studies in the University of Surrey, under the guidance of John Gilbert, and began the study of physical "spontaneous concepts," publishing his first paper on this subject (with Michael Watts) in 1981 (Gilbert and Zylbersztajn 1985; Watts and Zylbersztajn 1981). After his return to Brazil, in 1984, Zylbersztajn continued to develop this research line at UFRN and, after 1987, at the Federal University of Santa Catarina (UFSC).

The comparison between the students' concepts and the historical evolution of science became one of the main uses of history of science in physics education, in Brazil, for a significant period. This trend was soon linked to the work of Piaget and Garcia (1982) on the parallels between psychogenesis and history of science.[11]

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[11] There were some critics of this kind of parallelism, for instance, Franco and Colinvaux 1992.

The study of the students' previous concepts and of the strategies to produce conceptual change became more and more sophisticated during the decades of 1980 and 1990, with the development of analogies between science education and the ideas of Feyerabend, Laudan, Bachelard, and other philosophers of science.

In the 1990s, educational experiments developed by Anna Maria Pessoa de Carvalho and Ruth Schmitz de Castro introduced historical texts in secondary school classrooms, to explore the similarity between the student's concepts and the ideas presented in those texts (Castro and Carvalho 1995). Many students were stimulated by noticing the similarity between their own concepts and those of important scientists. The discussion of historical texts also helped in producing a conceptual change in the students. The texts and the description of their use were later incorporated in teachers training courses, showing a specific useful application of history of science in science teaching.

There were other different trends. Towards the end of the 1970s, another group of the University of São Paulo, including Luis Carlos Menezes, João Zanetic, and the graduate students Demétrio Delizoikov Neto and José André P. Angotti, endeavored to apply the educational ideas of Paulo Freire (Freire 1970) to science teaching, linking some of his ideas to Thomas Kuhn's views. Delizoikov, Angotti, and other educators put to practice this proposal during a stay in Guinea-Bissau, one of the countries where Freire had worked during his exile from Brazil, after the 1964 military *coup d'état* (Delizoikov Neto et al. 1980). The dissertations of Delizoikov and Angotti, supervised by Menezes, were completed in 1982 (Delizoikov Neto 1982; Angotti 1982). Although Kuhn's ideas had been a starting motivation, the stronger emphasis of those works is neither historical nor philosophical.

Menezes also supervised Alexandre José Gonçalves de Medeiros, who finished in 1984 his M.Sc. dissertation on the sociocultural and economic influences that acted upon the development of physics up to the end of the seventeenth century. As pointed out above, this line of social history of science had been strongly influenced by Marxist authors.

Although several researchers of USP involved with history and philosophy of science participated in projects that produced educational materials for secondary schools, those projects did not include the use of history and philosophy of science.

Since that time, the uses of history, philosophy, and sociology of science in teaching are a thematic area in graduate programs and conferences on physics and science teaching. There are several research groups devoted to this topic exploring different approaches and methodologies. Along the last years, several books and papers were published on this topic, attesting that history and philosophy of physics is embedded within physics education in Brazil since its very beginning. One strong trend is that several authors hold that the study of historical episodes of science can help students to form a more accurate view of the nature of science and to learn about scientific concepts.[12]

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[12] Assis (2008), Batista (2004), Braga et al. (2012), Carvalho and Vannucchi (2000), Forato et al. (2012), Greca and Freire Jr. (2003), Martins and Silva (2001), Pagliarin and Silva (2007), Rosa and Martins (2009), Moura (2012), Silva (2006), Silveira et al. (2010), Silveira and Peduzzi (2006), and Teixeira et al. (2012), Silva and Moura (2012).

70.6.2 Chemistry

The development of a research line in chemistry teaching, in Brazil, had its beginning at the University of São Paulo (USP). When this university was created, in 1934, a German chemist called Heinrich Rheinboldt (1881–1955) was invited to begin the chemistry department. Rheinboldt had a strong interest in the education of teachers and also in history of chemistry, having published in 1917 a study about Johann Baptist van Helmont. He was very influential in stimulating the study of history of chemistry and chemical education (Schneltzler 2002). Under his inspiration, Simão Mathias devoted himself to the history of chemistry, especially after retiring from the Chemistry Institute, in 1972, when he became a professor at the History Department and was responsible for the discipline of history of chemistry.

In the decade of 1960, Ernesto Giesbrecht, of USP, became involved with the translation and adaptation of the North American projects of chemistry (CBA, CHEMS). In the next decade, a group began to form at the Chemistry Institute of USP, under the leadership of Luiz Roberto de Moraes Pitombo and Maria Eunice Ribeiro Marcondes, devoted to the formation of chemistry teachers. José Atílio Vanin also began the development of activities of popularization of chemistry, with the help of students. Those activities finally led to the creation of the Group of Research in Chemical Education (GEPEQ), which is very active. In the decades of 1980–1990, the approach of the group was contributing to chemistry teaching at the secondary school level, with an emphasis in experimentation, relations between chemistry and everyday life, and the use of cognitivist proposals (Ausubel, Piaget).

Although there were some early activities related to chemistry education, such as those described above, the expansion of the area is strongly linked to the creation of the *Sociedade Brasileira de Química* (SBQ) (*Brazilian Chemical Society*) in 1978. During the first meeting of this society, there was a session devoted to the discussion of chemistry teaching, and interest in this line increased in the following years. The journal of this society *Química Nova* (*New Chemistry*) started the publication of papers on chemistry teaching in 1980.

At the same time, at the south edge of the country (State of Rio Grande do Sul), a series of regional annual meeting started in 1980: the *Encontro de Debates sobre Ensino de Química* (EDEQ) (*Meeting of Debates on Chemistry Teaching*), organized by Attico Chassot. In 1988 the *Brazilian Chemical Society* founded its Teaching Division and in 1982 began the series of biennial conferences called *Encontro Nacional de Ensino de Química* (ENEQ) (*National Meetings on Chemical Teaching*). In 1995 the *Brazilian Chemical Society* founded a new journal: *Química Nova na Escola* (*New Chemistry at School*), the main target of this publication being secondary school chemistry teachers.

One of the strongest lines of research in the 1990s was the study of previous concepts of students and the way of dealing with those ideas. The earlier idea that those spontaneous concepts should be transformed or replaced by the standard scientific concepts was given up by Eduardo Fleury Mortimer, who developed a new approach of conceptual profiles, inspired by Gaston Bachelard (Mortimer 1995, 2000).

The new attitude allows the students to keep their previous concepts, being aware of the difference between the scientific and popular cultures.

During the decade of 1990 the analysis of the epistemological beliefs of chemistry teachers led to the conclusion that they adopted a naïve empiricism and transmitted this attitude to their students. It became evident that the training of chemistry teachers should include not only the knowledge of chemistry but also its historical and epistemological features, as well as the social, economic and political context of the development of this science (STS approach).

Contributions from history and philosophy of science are not very common in research on chemistry teaching. Among several different approaches that can be found, we can point out an emphasis in the analysis of epistemological views presented in textbooks and by students and teachers and proposals of strategies to provide a more adequate view on the nature of science using historical studies of chemistry. The science, technology, and society approach is also deemed important, and historical examples (such as the development of dyes) are suggested to introduce this issue. Some of the works also claim the improvement of learning of chemical concepts using a historical approach.

Many works that cannot be classified as "research in chemistry education" should also be mentioned. From the 1990s onwards, several Brazilian chemists have published popular books on history of chemistry (Vanin 1994; Chassot 1994) and many papers on specific subjects. More recently, Juergen Heinrich Maar is producing a three-volume work on the history of chemistry (two parts have been published: Maar 2008, 2011). The production of papers on specific episodes of the history of chemistry has also provided the Brazilian teachers with some nice works that can be put into use in their educational practice.[13]

70.6.3 Biology

As noticed above, the BSCS project was introduced in Brazil in the 1960s. Besides many innovations, the project included a historical study of biological concepts. However, this did not lead to any stimulus for the development of studies of history of biology applied to science education in Brazil, at that time.

Brazilian educational projects related to biology teaching were produced from the decade of 1960 onwards. They attempted to produce textbooks with new content, together with laboratory materials. Until the next decade, the main concern was the production of teaching materials and the teaching training, and there was no concern with educational research in biology. Around 1990 the area begins to produce researches on spontaneous concepts of students and teachers and on the use of history and philosophy of science.

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[13] Among the articles devoted to the use of history of chemistry on education see, among others, Bagatin et al. (2005), Baldinato and Porto (2008), Chassot (2001), Farias (2001), Flôr (2009), Oki (2000), Paixão and Cachapuz (2003), Porto (2004), Tolentino and Rocha Filho (2000), and Vidal et al. (2007).

In the cases of physics and chemistry, the respective scientific institutes of the University of São Paulo (USP) played a relevant role in the development of the area of science education. The national physical and chemical societies also gave strong support to this area. In the case of biology, the situation was widely different. Research in biology education was strongly developed at the Faculty of Education of USP, especially under the leadership of Myriam Krasilchik – not at the Institute of Biology.[14] Besides that, since a *Brazilian Society of Biology* never existed, there was no association that could support the area. Indeed, there are several biological societies in Brazil, related to genetics, zoology, etc. but none that could assume the improvement of biology teaching as its concern.

In 1984 the Faculty of Education of USP began a series of conferences, called *Encontro Perspectivas do Ensino de Biologia* (*Meeting on Perspectives of Biology Teaching*). Although they did not have a national character, those events attracted researchers from other institutions, starting a process of organization of the area. The creation of the *Sociedade Brasileira para o Ensino de Biologia* (SBEnBio) (*Brazilian Society for the Teaching of Biology*) in 1997 led to a decentralization of the events, with regional conferences on biology teaching promoted at other states. The first *National Meeting for the Teaching of Biology*, organized by SBEnBio, occurred only in 2005. The journal of this society, *Revista de Ensino de Biologia* (*Journal of Biology Teaching*), started in 2007. In 2008, the *Brazilian Association for Philosophy and History of Science* (ABFHiB) created a Commission for Biology Teaching and produced a series of case studies for application in secondary schools.[15]

Up to 1996 the number of theses and dissertations on biology teaching was very small. In the last years of the twentieth century, there was a strong increase, parallel to the creation of the *Brazilian Society for the Teaching of Biology*, but not as an effect of this society (Teixeira et al. 2009). Around 1990 the area begins to produce researches on spontaneous concepts of students and teachers and on the use of history and philosophy of science.[16] The first works on the STS approach in biology education appeared a few years later.

Works using this approach usually stress the importance of introducing history of science in biology teaching to present science as a human construct, subject to mistakes, influenced by external factors, producing provisory knowledge. They denounce the inductive view of science, the idea that biology was produced by a few bright minds, and the view that science is the attainment of absolute truth. Those researches also emphasize the need to introduce history and philosophy of science in the teaching training. The STS approach is also recommended, adding the environment dimension. Besides discussion and recommendations, there are several

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[14] It is worth mentioning that the situation has changed along the last 5 years. Due to the Teacher Education Program of USP, the Institute of Biosciences hired professors on biology teaching and history of biology, and new similar positions for science teaching were created in other science institutes (Universidade de São Paulo 2004).

[15] Andrade and Caldeira (2009), Batisteti et al. (2009), Bizzo and El-Hani (2009), Carmo et al. (2009a), Brandão and Ferreira (2009), Martins (2009a), (2009b), and Prestes et al. (2009).

[16] Among others: Bastos (1998), Cicillini (1992), Martins (1998), Slongo (1996).

works that include the production, application, and analysis of teaching activities using history and philosophy of biology.[17]

70.7 National Educational Guidelines

The relevance of history and philosophy of science in science teaching was officially recognized, in Brazil, at the end of the twentieth century. In 1996, the Brazilian Ministry of Education (MEC) began an educational reform. The first official step was the promulgation of the *Leis de Diretrizes e Bases* (*Law of Brazilian Education Guidelines and Bases*), followed by a *Resolution* of the National Education Council that established the *National Curricular Guidelines for Secondary Education*, in 1998 (Brasil 1996, 1998). This *resolution* describes, in its tenth article, some of the abilities and competencies that the students should acquire in their study of mathematics and natural sciences, including:

> (a) To understand the sciences as human constructs, recognizing that they develop by accumulation, continuity or paradigm rupture, correlating the scientific development to the transformation of society; […] (i) To understand the relation between the development of the natural sciences and the technological development and to associate the different technologies to the problems that they intended to solve; (j) To understand the impact of the technologies associated to the natural sciences in the student's personal life, in the production processes, in the development of knowledge and in social life (Brasil 1998, p. 4–5).

The first of those items is directly related to the nature of science issues, associated to history and philosophy of science, and the other ones, to history of science and technology and science-technology-society issues. That document did not suggest any other roles for history and philosophy of science.

A group of educators, invited by the Ministry of Education, produced in 1997–1998 a document explaining how the general guidelines should be applied by teachers: *Parâmetros Curriculares Nacionais para o Ensino Médio* (PCNEM) (*National Curriculum Parameters for Secondary Education*) (Brasil 1997). This was followed by a more detailed complement, published in 2002: *PCN+Ensino Médio: Orientações Educacionais Complementares aos Parâmetros Curriculares Nacionais* (*Educational Complementary Guidelines to the National Curriculum Parameters*) (Brasil 2002). The sections of those two official documents concerning mathematics, physics, chemistry, and biology point out, at several places, the relevance of history and philosophy of science to science education.

The elaboration of the two documents on natural sciences and mathematics was coordinated by Luís Carlos de Menezes. For each discipline, the group provided

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[17] Among others, see Almeida and Falcão (2005), Batista and Araman (2009), Baptista and El-Hani (2009), Bastos and Krasilchik (2004), Caldeira and Araújo (2010), Carmo et al. (2009b), Carneiro and Gastal (2005), El-Hani and Sepulveda (2010), El-Hani et al. (2004), Goulart (2005), Justina (2001), Leite (2004), Meglhioratti (2004), Pereira and Amador (2007), Rosa and Silva (2010), Santos (2006), Santos et al. (2012), Scheid et al. (2005), and Slongo and Delizoikov (2003).

specific instances of the use of history and philosophy of science, especially related to the issues of the nature of science and science, technology, and society. The previous official documents understood the contextualization of science education in the sense of the cognitive approaches to education. The group interpreted the contextualization in a much broader sense: "In general terms, contextualization in science education includes competencies related to the insertion of science and its technologies in a historic, social and cultural process and the recognition and discussion of practical and ethical features of science in the contemporaneous world […]" (Brasil 2002, p. 31). The *Educational Complementary Guidelines* (PCN+) provide a large number of specific instances that can be used by teachers in addressing those issues.

Besides those features related to history and philosophy of science, there were many other new proposals that cannot be described here. If the guidelines could be put into practice, they would greatly improve science teaching, in Brazil. Unfortunately, more than 10 years after the educational reform and the publication of the above-described documents, one cannot recognize any definite transformation in science education. Secondary school science teachers could hardly understand all the changes that have been recommended. One can attribute this failure to a lack of effective public policies to improve the school system as a whole. One central aspect that is rarely addressed is the fact that teachers had no adequate training for coping with the new proposals that could help them to attain the new aims.

70.8 Conclusion

Nowadays, the relevance of history and philosophy of science in science education is widely recognized in Brazil. Although the effective classroom practice has not yet incorporated its use, the official educational guidelines are stimulating its development. A large number of books and papers, theses and dissertations, have been produced on this theme. This approach is an important trend in graduate programs and in educational conferences.

Two specific meetings on this subject were held in Brazil, in 2010: the *8th International Conference for the History of Science in Science Education* (ICHSSE) and the *1st Latin American Conference of the International History, Philosophy and Science Teaching Group* (IHPST-LA), with the participation of about 150 researchers (Silva and Prestes 2012). Some specific books on the subject, providing information and suggestion of classroom activities, were published in recent years. There is also an increasing international and regional collaboration.

The Brazilian contributions in this area are not well known worldwide, because most works are published in Portuguese. Although it is relevant to participate in global conferences and projects and to publish in other languages that can reach a wider public abroad, it is very important to produce works in Portuguese for local use. The vast majority of secondary school teachers cannot understand books and papers in English, and even those who can do it prefer reading works published in our national language.

There are several types of publications in this area. The academic ones (those presented at conferences or published in scholarly journals and books) describe the several approaches and defend (or criticize) their use; they review researches published abroad and in Brazil; they analyze textbooks; they present surveys of the concepts of students and teachers concerning the nature of science and other subjects related to history and philosophy of science; they provide information about history and philosophy of science that can be used in science teaching; they describe specific developments of syllabi, texts, and other educational materials applying history and philosophy of science in education; they report classroom experiments using history and philosophy of science; and they present proposals of new initiatives in the field, such as teaching learning sequences based in application of history and philosophy of science in science education (Peduzzi et al. 2012). Nowadays, the focus of history and philosophy of science in science education is the discussion of the nature of science and science, technology, society and environment issues. The uses of history of science to improve the learning of scientific ideas, to increase the motivation of students, its intrinsic cultural value, and other uses that were proposed in the 1970s and 1980s, are nowadays seldom mentioned.

The vast majority of authors of the abovementioned academic works are either university professors or graduate students. Most of this production will never reach in-service science teachers, but might be used for preservice teaching training at the university, or in specific courses for in-service teachers.

On the other hand there are publications targeted at in-service teachers (and also students), such as the journals that have already been described (*Revista do Professor de Matemática*, *Química Nova na Escola, Física na Escola*) and books. Those journals have a wide penetration, but their function is mainly informative. It is doubtful that they have contributed to effective changes in science teaching, because they only contain short papers. There are many books on history and philosophy of science published in Portuguese. However, teachers interested in this subject usually read popular, out-of-date books that reproduce the old views on the nature of science.

There is a shortage of educational materials using history and philosophy of science in the secondary school classroom. As described above, as a rule science textbooks include mistaken information about history and philosophy of science. There have been attempts to produce supplementary texts on history of science for use by students, but their effective utilization has been very limited.

Much remains to be done in consolidating the effective use of the history and philosophy of science in Brazilian science education. Nevertheless, it is possible to say that there is a solid ground, in research and graduate courses; there is clear official interest in the use of history and philosophy of science in education; there is a growing awareness and interest in this subject by teachers; there is a pressure by the Ministry of Education upon publishing houses in order to improve the quality of history views on nature of science in textbooks; in a nutshell, there are nice conditions to take off and fly. Of course, government support is essential and is sometimes unavailable; but many initiatives that depend only on researchers can start a snowball effect and produce important results.

It is necessary to consider the complexity of the education system in order to create a successful implementation of history and philosophy of science at schools. There is a gap between research and practice to connect curricular innovation with teaching practice; it is not restricted only to history and philosophy of science (see, among others, Pekarek et al. 1996; Pena and Ribeiro Filho 2008; Höttecke and Silva 2011). Thus, working collaboratively with in-service teachers is essential. In order to foster the use of history and philosophy of science in science education, it is important to take the teachers' perspective into account; otherwise curricular innovations will be hard to implement.

The introduction of disciplines in teachers training courses that combine scientific content and historical and philosophical issues with didactical aspects is highly desirable. It can allow future teachers to develop some of the needed skills to implement this approach in practice and to develop an awareness of the real worth of the use of history and philosophy of science in their teaching (Höttecke and Silva 2011).

It is also important to establish stronger cooperation between scholars in this field: one swallow does not make a summer. Collaboration may occur at several different levels. The creation of a national society for history and philosophy of science in science education, together with a specific journal and periodic meetings, might enhance the visibility of the area and provide a better forum for debate of researches and for the planning of national strategies. This does not mean that researchers working in this area should keep apart from other societies, of course. The creation of national databases for dissertation, theses, electronic versions of books, conference proceedings, and papers would be a nice instrument both for the improvement of research and for the dissemination of works. A teamwork including many groups and institutions could propose and lead ambitious projects – both research projects and educational ones. In a lower scale, a researcher producing new educational materials should ask the help of other researchers, from different institutions, to test and comment on his/her work; a researcher doing a survey of concepts on the nature of science at one institution should ask the cooperation of colleagues from other institutions to do a similar survey at other places, to compare their results. Researchers should think great: could my current work improve if I asked other people to collaborate?

Another front to be developed is a combination of research and application. We mean *real* application, such as posting on the Internet educational materials, together with suggestions for their use and additional materials (such as a video uploaded to *YouTube*). Of course, quality should always be a concern – both in research and application. A careful transposition can produce high-quality popularization and educational materials. The combination of those last two attitudes – trying to cooperate and to be useful in a broader sense – could greatly improve the situation in the area.

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Chapter 71
Science Teaching and Research in Argentina: The Contribution of History and Philosophy of Science

Irene Arriassecq and Alcira Rivarosa

71.1 Introduction

The analysis of the possible contributions to physics education made by the history and the philosophy of science constitutes a formidable task. Before we go on, a short note about some abbreviations that will be used throughout the text. From now on we will abbreviate the history of science as HS and the philosophy of science as PS; whenever we refer to both areas together, we will write HPS. In order to understand how complex this task is, we should first identify the multiple theoretical aspects that converge here.

On the one hand, physics as a scientific discipline has among its main objectives the aim of explaining, understanding and predicting natural phenomena. These objectives are achieved by intervening in those phenomena using specific methodologies and also specific language to communicate findings.

On the other hand, HPS, in spite of not strictly being considered a meta-science, is a hybrid field constituted by contributions from different meta-sciences, or second-order criteriology, which have other scientific disciplines as their objects of study (Losee 1972; Klimovsky 1994). HPS is a theoretical reflection of scientific knowledge and activity from an internalist and logical-linguistic perspective which focuses on the study of the processes, conditions and results of innovation, justification, systematization, application, evaluation and communication in science (Adúriz-Bravo et al. 2006).

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More recently, a line of work under the name ‘nature of science’ has developed. It is made up of a group of meta-scientific laws which are valuable to natural science teaching, and it is precisely the ‘nature of science’ which constitutes its object of study.

The term ‘meta-science’ refers to all the disciplines which have science as their object of study: epistemology, history of science and sociology of science, among others. These disciplines provide different frameworks for the study of science, the aim of which is to answer questions such as ‘what are scientific knowledge and scientific activity like?’, ‘how does science change through time?’, ‘who have been the most relevant scientists in history and in what way are they relevant?’, ‘which are the values the scientific community adheres to?’ and ‘how does science relate to the other disciplines (humanities, technology, art) and other ways of interpreting the world (religion, myths, even popular beliefs)?’ (Aduriz-Bravo 2005).

Multiple contexts coincide in the area of science education: a discipline to be taught, theoretical frameworks, processes for teaching and learning, teaching proposals, teaching contexts, conceptions of such a discipline and its own nature on the part of both the teachers and the students, the teachers’ background, etc. Research into these aspects of HPS throughout its evolution has not always considered the possibility that the analysis of the topics of this subject could contribute to physics education. However, in recent years, this has started to be taken into account for the design of syllabuses, in light of the contributions made by researchers like Salomon (1988) and Lakin and Wellington (1994), who consider that the teacher’s view of science, whether explicit or not, affects what and how he/she teaches. In connection with this opinion, many other authors such as Lantz and Kass (1987), and Duschl (1997), state that a science teacher’s background should involve not only a science but also aspects related to the nature of science, such as knowledge about its purposes, methods and its relationship with technology and society.

In a time when scientific literacy has become one of the goals of science education in many countries, it is of paramount importance to gain a deeper understanding of the history and nature of science in order to achieve such an objective. It is expected that a scientifically literate individual should be able to distinguish between scientific and non-scientific knowledge, science and pseudoscience, to know the limits and scope of science as well as what science can or cannot explain and to identify the scientific methodologies. As an individual and as a member of a particular society, he should also be able to tell what is relevant to the scope of science, taking the positive as well as the negative aspects into account.

However, the concept of the nature of science (NOS), as Acevedo-Diaz and colleagues (2007) point out, is complex and dialectical and therefore difficult to define with accuracy and by general consent. Specialists often discuss descriptions and representations of the NOS which are as dynamic as scientific knowledge itself, and so it is impossible to support the idea of only NOS capable of representing either this knowledge or all the scientific disciplines. Therefore, any representation of the NOS will be partial and will compete with other incomplete representations.

With regard to science didactics, even though there is consensus about the importance of the NOS in science education (Bell et al. 2001), the means of achieving their own objectives are not clear.

There exist at present several international groups that study the applications of the NOS to science education at different levels. Among these groups one of the most important is the International History, Philosophy and Science Teaching Group (IHPST). This group has been holding conferences since 1989 and has encouraged international magazines with great prestige within the scientific community and among science education teachers – such as the *International Journal of Science Education*, among others – to dedicate special editions to the NOS and its relation to science education. Another major landmark was the creation of *Science & Education*: *Contributions from History, Philosophy and Sociology of Science and Mathematics*, which since 1992 has promoted the inclusion of history and philosophy of science and mathematics courses in science and mathematics teacher education programmes. Moreover, it promotes the discussion of the philosophy and the purpose of science and mathematics education and their place in, and contribution to, the intellectual and ethical development of individuals and cultures. It is associated with the International History, Philosophy and Science Teaching Group, and Michael Matthews is its editor.

The First IHPST Latin American Conference was held in 2010. This conference focused on the presentation and discussion of papers about the use of history and philosophy in science education, in accordance with the guidelines drawn up by the IHPST group for international conferences.

This chapter analyses the historical evolution of the HPS in connection with science teaching and learning, the different lines of research that have developed over time and some examples of teaching proposals – aimed at students, teachers and trainee science teachers – which were designed by taking research results into account. A critical analysis of the present situation regarding the incorporation of the HPS in science education is carried out, and some ideas are suggested in order to make progress in this direction. More precisely, the last two sections evaluate the situation in Argentina with regard to the incorporation of HPS contributions into physics and biology education. Some of the aspects analysed are the underlying epistemological features in educational laws and the natural science curriculum design at secondary level in Argentina, the incorporation of HPS into research and the dissemination of HPS contributions to physics teaching among in-service teachers.

71.2 Design, Implementation and Assessment of Teaching-Learning Sequences That Incorporate Contributions from the HPS

Teixeira and colleagues (2009), in a thorough and methodologically rigorous work, investigate teaching experiences of applying HPS in physics classrooms, with the aim of obtaining critical and reliable information on this subject.

The vast majority of the studies selected for analysis support the idea of similarity between students' spontaneous understanding of scientific concepts and the historical development of these concepts. The aim was to obtain a conceptual change, despite the large amount of criticism found in the literature about this type of approach. In spite of the presence of a variety of teaching strategies based on HPS, comparatively few of them provided the pedagogical references to justify the use of these strategies, and few were concerned with assessing the students' prior knowledge of HPS.

The studies analysed by the authors presented various ways of utilizing HPS in the teaching of physics: in relation to teaching objectives (learning concepts, nature of science (NOS), attitudes, argumentation and metacognition), in relation to teaching strategies (integrated with the subject of physics, integrated with another teaching strategy and not integrated) and in relation to didactic materials (historical narratives, biographies, replicas of historical experiments, historically contextualized problems and stories of scientists' lives).

The results revealed the occurrence of positive effects in the didactic use of HPS in the learning of physics concepts, despite there being no consensus about this, and they also indicated a lack of agreement about the occurrence of conceptual change. Greater research efforts are therefore needed to investigate these aspects, especially when the aforementioned limitations in research procedures are taken into account. In the same way, no consensus was found as to how HPS promotes improvements in the students' attitudes to science, which also leads the authors to conclude that this subject needs further investigation.

This type of approach appears to promote a more mature vision in respect of the students' understanding of NOS, which should be taken into consideration when planning curricula and/or physics teaching strategies. Favourable results were also found when looking at the effects of the didactic employment of HPS on the areas of argumentation and metacognition, despite the dearth of studies in the analysis dealing with these areas. Potentially important areas are being explored which warrant a higher position on the HPS-based physics teaching research agenda.

A recent thesis (Arriassecq 2008) dealt with the problem of meaningful teaching of the special relativity theory (SRT) at secondary school level in Argentina. Several studies have been carried out, focusing on the epistemological difficulties presented by the content of the SRT itself, the teachers' difficulty in approaching the task of dealing with such a theory at that level and the textbooks that both teachers and students would have as a teaching resource. The results of such studies showed that there is a wide gap between the proposals presented in the documents from the ministry, as well as some research reports, and their actual practice in class. In order to narrow this gap, a teaching proposal was developed in which the SRT is approached within a historic and epistemological context.

Part of the design of this teaching proposal – designed within a framework that comprises epistemological, psychological and didactic aspects – consisted of producing written material (in textbook format) to be used by teachers and students, taking into account the deficiencies identified through this approach.

Several studies conducted before the design of the teaching proposal and the supplementary teaching material for its implementation adopted an approach that assigns the use of the history of science and epistemology for the design of concrete class proposals, a role as important as that of working within a psychological and didactic framework. This contextualized approach places great conceptual emphasis on the topics discussed, so that the historical-epistemological discussions can be meaningful to students.

The use of the history of science and epistemology is considered to allow, among other aspects, the determination of the epistemological obstacles that serve as a guide for the selection of the relevant content to be taught as well as to favour the discussion of the production of scientific knowledge, the role of the social and cultural context at the time in which that knowledge is developed and its impact within and outside the scope of science. The aim should be to eradicate stereotypes about science that keep students away from this discipline.

With regard to the epistemological aspect, the thesis draws on elements of Bachelard's epistemology (1991) to produce an epistemological analysis of the content of the SRT (Arriassecq and Greca 2010). This analysis defined the central concepts that students should learn in a meaningful way. These are space, time and notions related to reference systems, observer, simultaneity and measurement, which are essential for a relativistic understanding of space-time.

The results of the assessment of the implementation of the teaching proposal show that the acquisition of key concepts of the SRT seems to be much better than those obtained when the SRT is approached in a 'traditional' way, in which the traditional textbook is the main teaching resource used by the teacher (Arriassecq 2008; Arriassecq and Greca 2010).

As for the text produced as part of the design of the teaching proposal, it treats in greater depth a topic that, despite its importance, has not been sufficiently investigated within the area of physics education in Argentina. In addition, it has been produced within an innovative theoretical framework that comprises epistemological, psychological and didactic elements.

71.3 Researches on HPST in Latin America

In Latin America, Brazil was the first country to consolidate the science education area and then to incorporate the study of the contributions made by HPS as a line of research within science education itself. Researchers in the science education area in Argentina have been establishing links with researchers in Brazil since this area started developing in this country. This has been done on the one hand through the guidance given to Argentinean researchers on their theses by prestigious Brazilian researchers such as Marco Antonio Moreira, from UFRGS. On the other hand, it has been accomplished by Argentinean researchers spending time at Brazilian institutes and universities as well as by disseminating and publishing Argentinean research projects in pioneering magazines issued in Brazil.

As Villani and colleagues (2010) point out in a thorough review, the development of science education research in Brazil was very similar to that which took place in many other Western countries, at least until the early 1990s. Research in science education first appeared systematically 40 years ago, as a consequence of an overall renovation of the field of science education. This evolution was also related to the political events taking place in the country.

After this period, Brazilian researchers became less dependent on foreign sources, and original lines of research were introduced, differentiating the development of this period from the one preceding it. Finally, the role of the history and philosophy of science appeared as an important intermediary during the stabilization process, not only unifying a great number of the research projects carried out during that period, but also serving as a means of participating in the political and ideological arena.

During the first phase, which included the founding of the area, the history and philosophy of science played only a limited role in the process of institutionalizing science education research. On the one hand, articles and books showed thinking based on the simplistic idea that the mere knowledge of the history of science would in itself stimulate students' motivation and facilitate their learning of scientific concepts. Other books and articles seemed unrelated to teaching and showed very little progress in exploring the history and philosophy of science more efficiently in the classroom. However, the community of researchers involved in educational projects considered that contributions from the history of science were very important, including its practical results, such as the production of teaching material to complement projects for physics teaching.

During the 1970s, some of the researchers went on to study further and publish a history of science that included the connections and commitments between scientific development and economic and political power. This task was considered a way to combat the military dictatorship then in power in Brazil and thus implicitly to denounce the pact between universities and the government.

The contribution of the history and philosophy of science to the consolidation of the area was stronger during the 1980s. First, journals founded during this period disseminated their ideas to others who were also interested in the history and philosophy of science. The *Journal of Physics Teaching* was launched in 1979, but until 1993 it had no specific section dedicated exclusively to the history and philosophy of science. Nonetheless, each edition contained individual articles dedicated to the theme. In contrast, right from its beginnings in 1984, the *Santa Catarina Journal of Physics Teaching*[1] included a section entitled 'The History and Philosophy of Physics'.

Another important contribution came from abroad, where the students could develop studies about the history and philosophy of science.

During the 1990s, a more theoretical contribution of the philosophy of science also fostered the development of variations in the Conceptual Change Model, giving special emphasis to other philosophers besides Kuhn and Lakatos. Specifically, some researchers developed analogies between science learning in school and the development of science as understood by Feyerabend, Laudan, Popper and Bachelard. Villani (1992) explored the flexibility of Laudan's approaches to the progress of science

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[1] *Revista Catarinense de Ensino de Física.*

(Laudan 1984) for understanding the changes that take place in students' ideas in school. Based on Bachelard's idea of 'epistemological profile' (Bachelard 1978), Mortimer (1995) proposed a new version of the same concept, which became known as conceptual profile. He posited that cognitive evolution intrinsically joins old ideas with new ones and considered that teaching should promote a change in students' profiles by broadening their spectra of useful ideas.

During the last phase of the institutionalization process of science education research, two trends were developed in relation to the history and philosophy of science: towards reforming the cultural scientific knowledge on which high school education was based and towards training teachers to develop corresponding lines of research.

The first trend was a reform in scientific knowledge, focused on information concerning the genesis of conflicts and the evolution of scientific theories as well as on successes and failures. The work was carried out at schools themselves. But time should also be devoted to reflection on the presuppositions, images and basic intuitions of scientific advances. The training of science teachers should foster the acquisition of this knowledge for two purposes: first, from the cultural standpoint, to enrich the quality of the content to be taught and, second, to adhere to the methodological requirements that were considered the most appropriate.

In the second trend, researchers in the history and philosophy of science comprised a specific group, with their own graduate and postgraduate courses, journals and congresses.

The researchers' work became more technical (Martins 2000; Pietrocola 1992), their methodology became more precise, and case studies were included, such as information about Becquerel (Martins 1997) and the alchemist Sendivogius (Porto 2001). At the same time, efforts were made to keep in contact with the area of science teaching through attention to studies such as Newton's theory of colours, which is full of technicalities but useful for teaching purposes (Martins and Silva 2001).

In the case of Argentina, as Orlando and colleagues (2008) point out, the physics teachers' community received great encouragement in the 1980s. More precisely in 1983 in Cordoba, the physics education meeting (REF),[2] which attracts more than a thousand teachers of this subject matter, was held for the first time in several years. At that meeting the Association of Physics Teachers of Argentina (APFA)[3] was created. This association would be in charge, among other things, of organizing periodical meetings and events. The success of such events was reflected not only in the number of people present and the variety of topics that were discussed but also in the increasing number of research projects presented. Throughout the years the increasing number of research papers that were presented in that meeting showed the need for the creation of another meeting focused on research on the area. This new meeting was called the 'Symposium on Physics Education Research' (SIEF), and the first one took place in Tucumán in 1992.

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[2] Reunión de Educación en Física.

[3] Asociación de Profesores de Física de la Argentina.

APFA is responsible for summoning researchers to an alternate REF and a SIEF every 2 years. The researchers' community has been growing in number and its tasks have become more specific. At the beginning the number of researchers with a doctoral degree was small, and this was done either abroad or under the guidance of foreign supervisors. Nowadays it is possible to form human resources and take postgraduate courses in our country.

The growing number of projects presented at the various symposiums throughout the years would reflect the researchers' increasing interest in working on topics related to physics education in the different education areas.

The increase in the number of articles that follow those criteria for research work since the first SIEF up to the present shows growth in the construction of knowledge in the field of physics education as well as an incremental change in specific training for researchers in science education.

It should be noted that the research projects presented at the symposiums deal with heterogeneous topics. Most of them refer to problems connected with teaching, learning, curricular aspects and context problems or about the teacher training or with educational transfer. A small percentage of them deal with topics related to theoretical frameworks, epistemological aspects or methodological development. However, there has been an evolution in research related to the use of HPS as a theoretical framework. This will be addressed further.

There are still some questions to be answered: Have the curricula – especially secondary school curricula – included HPS? Do the curricula of colleges of education provide for training in HPS? What happens with practicing teachers who as undergraduates did not have the chance to become familiar with the contributions made by the HPS to science education? Do class textbooks, both the teachers' and the students', incorporate such contributions? If they do, how do they do so? Are there any teaching proposals based on research results?

The next section evaluates HPS contributions to science education in Argentina. Some of the aspects analysed are the underlying epistemological features in education laws and natural science curriculum design at secondary level in Argentina, the incorporation of HPS in research and the dissemination of HPS contributions to physics teaching among in-service teachers.

71.4 Incorporation of Contributions from the HPS into Physics Education in Argentina

This section evaluates the incorporation of HPS into physics education in Argentina. The analysis focuses on education laws and on curriculum designs – particularly at secondary level – on the most relevant aspects of the curriculum designs for physics teacher training and on research and articles published in *Physics Teaching Magazine*, which is a publication issued by the Association of Physics Teachers of Argentina (APFA).

The selection of the materials analysed was based on the fact that the APFA magazine is the main channel of communication between researchers and teachers.

It should be noted that most of the researchers who attend national events and publish in the aforementioned magazine also attend international events and publish in prestigious magazines in other countries. However, only a small number of teachers have access to them.

71.4.1 Epistemological Features Underlying Educational Laws and Curricular Designs for Natural Science Teaching at Secondary Level in Argentina

This section analyses several national education laws that have been, and are still, enforced in Argentina, the regulations on some of these laws which provided a frame of reference at certain times in Argentinean history and in curriculum designs – for natural sciences at secondary level. Curriculum designs were formulated by the Ministry of Education and the Buenos Aires Provincial Ministry of Education in order to define possible epistemological conceptions in the history of Argentinean education, based on the stances underlying, sometimes implicitly, the aforementioned ministry documents (Framework for the Oriented Bachelor in Natural Sciences 2011).[4] This province was chosen because it accounts for 33 % of all the educational institutions of the country and accounts for 38 % of students.

Society has changed throughout the history of the country, from an economic, as well as a political and a cultural, point of view. Education policies are therefore expected to evolve and create favourable conditions for teachers, students and institutions so that objectives are achieved, adjusting to changes in society.

Particular consideration is given to whether there has been an evolution in the epistemological criteria that promote certain models for natural science teaching at secondary level and the development of notions, not only about science but also regarding scientific activity in different types of secondary schools. Furthermore, the aim is to identify certain characteristics present in the evolution of educational laws and in curriculum designs that may indicate an evolution from the so-called standard epistemologies to nonstandard ones.

The descriptive analysis is based on the identification of the characteristics of standard and nonstandard epistemologies in the following documents:

– The four national education laws: Law 1420 dating from 1884, Law 4874 from 1905, Law 24195 from 1993 and Law 26206 from 2006. Each was duly ratified and promulgated at a different time in Argentinean history, which means that each was conceived within different social, economic, political and cultural contexts. Only in the last two laws are there explicit references to epistemological debates.

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[4] Marcos de Referencia. Educación Secundaria Orientada. Bachiller en Ciencias Naturales. Aprobado por Res. CFE N° 142/11. Consejo federal de Educación.

- Two magazines: *Annals of Education of Buenos Aires Province* and *of Santiago del Estero Province*. Since, in the past, curriculum designs were not developed, State guidelines on teaching practice are only found in this kind of magazine on education.
- National and Buenos Aires Province curriculum designs for natural sciences. This province was chosen because it includes 33 % of the educational institutions in the country and 38 % of the students.

The analysis focuses especially on education laws and the corresponding curriculum designs at the secondary level.

Law 24195, dating from 1993, sets the guidelines for the national educational policy under the so-called Education Federal Law (EFL) and determines the structure of the educational system as consisting of early education; basic general education; the 'polymodal' level, with final (preuniversity) oriented cycles, among which is the natural science-oriented one; and higher and postgraduate education. The objectives of each of these levels are also defined in the different articles of the official curricular document. The regulatory style of the previous laws was abandoned in order to extend compulsory education to 10 years.

With regard to teachers, their rights and duties are established in Art. 46 and 47 of the EFL. The pedagogical and curricular guidelines mention academic freedom and freedom of education.

This law is accompanied by a national curriculum design, and each province develops its own with the different polymodal orientations.

In the document entitled 'Curricular Support Document N°1' (Petrucci 1994), about the natural sciences area – in particular, physics curriculum design in Buenos Aires Province – the author states that the document '… is a useful theoretical support when planning, implementing and assessing teaching practice …'. Teaching is considered a professional practice in which theoretical foundations underlie decisions, and therefore there are neither recipes nor methods to implement the teaching-learning process.

The view of science expressed here contradicts the traditional one which considers that science uses a unique method consisting of a 'recipe': several steps to obtain a product. Science is regarded as '… an open process, the stages of which are determined by the issues under study, the aims of the study, the historical context and the interests of the community'. As regards the way in which research work should be presented, the document states that '… according to present epistemological conceptions, scientific knowledge is built through a process of development of theories and models that aim to give meaning to a reference experimental field'.

In addition, the document recommends some authors who, based on the present theoretical framework for science teaching, stress the dynamic and provisional character of scientific knowledge, highlighting therefore its dependence on the historical context (Kuhn 1962).

The latest law, the National Education Law, sanctioned in 2006, modifies the organization and selection of the curriculum contents of the national education system. Four levels of education were established, early, primary, secondary and upper secondary/higher, whereas the period of compulsory education was increased to 13 years.

The national curricular design corresponding to this law refers to that regarding the natural sciences orientation within upper-secondary level. In the introduction, teachers are asked to present science '… as a social construction that is part of culture, with its own history, communities, agreements and contradictions …', to treat models and scientific theories as attempts to answer real problems and to take into account the role specific teaching methodologies play in understanding teaching-learning processes.

One of the general objectives is to form scientifically literate citizens who, during their school years, develop both scientific knowledge and a view on scientific activity.

In present designs, HPS takes on a different status, as the core thematic contents include science history and philosophy in order to approach the subject within its own curricular area at secondary level.

To sum up, the epistemological characteristics underlying educational laws and documents regarding natural science teaching at secondary level in Argentina have evolved since the first laws were sanctioned. They have developed from a teaching approach with positivist characteristics to models underlaid by nonstandard epistemological conception.

This evolution of the view on science promotes at the same time a change in the science teaching and learning approach, offering new roles for teachers and students, from a model in which the student is 'recipient' of knowledge 'imparted' by the teacher to one in which the student 'builds' 'academic knowledge' through the teacher's mediation.

71.4.2 The Incorporation of the HPS in Teacher Training

The general guidelines that physics teachers follow to learn topics of epistemology are derived from the regulations laid down by the organs responsible for education policies at the different levels of education in Argentina. In her thesis, Islas (2010) compiles all the documents that give advice on the incorporation of the HPS into the syllabuses of physics teacher training colleges.

The document '2008-Science education year' extracts the main points of the Report of the Argentinean National Commission for Improvement in Natural Science and Mathematics Education. The report stresses

> the need to overcome both the simplistic views on science and scientific work as well as those views of scientific work as something extremely difficult which lead to school failure. […] At the same time the program aims at arousing interest in those disciplines that follow from understanding what producing science and producing mathematics mean, their usefulness and importance for citizenship; at demystifying the process of knowledge development for students and teachers at different education levels, encouraging them to value it as an activity for social construction; at promoting future scientific vocations.

In the recommendations section of the document, those objectives are translated into some suggestions that are transferable to teaching practice. It is recommended that the different aspects of scientific knowledge should be taken into account, some of which are 'its empiricism, the need to build models, compulsory debate and discussion of the results and their interpretations'.

There are other points in the document regarding classroom work, of which it is worth mentioning the following one:

> Generally, in order for the students to build solid knowledge there should be experimentation, high frequency of questions, socratic dialogue, and rigorous, logically sound and simple reasoning. All these are characteristics of "proper thinking" in the science class. But they are also distinctive characteristics of scientists' thought when doing research.

Some lines below, in order to differentiate the contexts where knowledge is developed (the class and the researchers' community), it is stated that 'the most significant difference between both activities is that, whereas the scientific community generates new knowledge on the borderline between the known and the unknown, students in class build concepts that, despite being new to them, have already been validated by science'. Finally, it is worth pointing out that the Report of the Argentinean National Commission for Improvement in Natural Science and Mathematics Education states that one of the obstacles that have been detected in the diagnostic is the 'stereotyped picture of science and scientists, also shared by teachers'.

Most of the professors who are members of universities or state institutes have some curricular time at their disposal to study topics related to the HPS. Moreover, all courses include time for seminars in which it would be possible to approach topics connected with the construction of scientific knowledge.

Islas (*op. cit.*) has also done a review of the syllabuses, taking into account, apart from the list of contents, other elements such as the bibliography, the objectives of the subject and the requirements for passing the subject.

A characteristic that all programmes under analysis have is that they include nonstandard epistemologies. Even more, the section entitled 'tendencies among contemporary epistemologies', which appears in almost all syllabuses, is considered an indicator of the presence of innovating explanations. Authors like Kitcher, Giere, van Fraassen, Habermas and Gadamer appear in the references together with the more common ones like Lakatos, Feyerabend, Laudan, Toulmin and, to a lesser extent, Bachelard.

71.4.3 The Communication Among In-Service Teachers with Regard to HPS Contributions to Physics Teaching

The magazine *Physics Teaching,*[5] first published in 1985, is an undisputed reference on this issue at every level and is also a vehicle for communication among the members of the Association of Physics Teachers of Argentina.

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[5] *Revista de Enseñanza de la Física.*

The magazine has been published twice a year since 1992, and there are some special issues, with research articles, proposals for the classroom, reflections, notes and information on different aspects related to physics and physics teaching. It makes possible the communication of research works in the area of science education, providing insight into theoretical foundations, analysing the state of the art and making headway in understanding significant issues. It provides elements to enhance teaching practice, allowing the publication of teaching proposals, discussion of particular activities and analysis of experiences. It promotes events of interest, and it offers information and news that help members of APFA, as well as any readers, to keep up to date.

Three publishing teams have been in charge of the magazine during its 27 years of existence. The first one was in charge from 1985 to 1992, the second from 1993 to 2002 and the present one from 2003. The same spirit has been present in all of them, and it is possible to find articles that match the objectives mentioned above. However, the organization of the magazine has gone through different changes.

The first issues did not have permanent sections. During the second publishing period, the following sections were introduced: research and development, teaching issues, physics topics, history, science philosophy, information and news. Not all these sections were present in every issue and were replaced by others such as laboratory work and extracurricular activities.

The magazine now has permanent sections in all the issues. Each section is briefly discussed below so as to analyse those that deal with HPS contributions.

The 'Research' section includes articles on education research, related to teaching and learning of physics and other experimental sciences in general. It covers the incorporation of empirical research that answers paradigms and diverse approaches, as long as this is carried out with scientific rigour and systematicity, the development of theoretical frameworks, advances in methodology or revisions that deal with the state of the art on topics regarding research in science education. The 'Proposals' section includes articles offering teaching alternatives, innovations and curriculum formulation, among other topics, in connection with the teaching of physics and other experimental sciences at different levels. It may include contributions made in order to integrate physics with other sciences, specific classroom proposals and analysis of the curriculum and of resources. In the 'Essays' section special thematic articles are published (articles on physics topics, on the science-technology-society-environment relationship, philosophical and epistemological reflections, historical accounts, description of projects or programmes, etc). The 'Miscellaneous' section deals with discussions of problems, challenges and paradoxes, comments on books and/or software, teaching materials on the web, projects, classroom resources, etc. Finally, the 'News' section includes information on events and news of interest, workshops, development and information about postgraduate level courses, thesis abstracts and book reviews.

In the second period of the magazine, two types of articles coexist in the 'History' and 'Science Philosophy' sections. On the one hand, there are those that have been written by teachers and physics researchers who have taught or done research in this subject at different levels of education. Even though they lack a formal education in history and epistemology, they have been in a way pioneers in the incorporation of such debates in teaching. The first issue in 1997 featured an article in this respect written by Dr. Alberto P. Maiztegui – for many years president of the National Academy of Sciences and without any doubt remembered for his contributions to science teaching: his physics books for students and teachers, the promotion of science fairs in Argentina and the steady support to these topics that he provided from IMAF (nowadays FaMAF) and later the National Academy of Sciences. The article was entitled 'Archimedes and Hieron's crown' and was based on the well-known anecdote that describes Archimedes running naked around the streets of Syracuse exclaiming '¡Eureka! … ¡Eureka!' because of the joy he felt when finding a solution to the scientific problem he was working on. The article develops a series of detailed calculations, in connection with the problem in question, which are not frequently found in secondary textbooks. It should be noted that the article cites a source where the anecdote can be read, contrary to other texts that try to incorporate 'historical cartoons', without any mention of sources, only because students may find them attractive.

In the same issue, Guillermo Boido published the article 'The reconstruction of experiments in the history of science: Galileo under discussion' which states that the reconstruction of experiments carried out by scientists in the past has contributed to a better understanding of certain historical episodes and that this method has gained popularity especially when applied to Galileo's work, even though the results have received controversial interpretations. The possibilities and limitations of experimental history are explored, and there is a brief analysis of the state of the discussion – at the end of the 1990s – on the character of Galilean science in light of the reconstruction of some of his experiments. Prof. Boido does research into epistemology and science history and has been associate editor of the prestigious Argentinean scientific magazine *Science Today.*[6] The professional profile of this author is clearly different from that of the author of the article mentioned above. This article focuses on science history research problems. At the same time, the editors point out that the article

> … is valuable material for our readers, particularly now that science history demands attention on the part of science education and a better place in the curricula in general, both at secondary and higher education levels.

Finally, in the present stage of the magazine, there has been a significant change with regard to the kinds of publications that consider the incorporation of HPS contributions to science and particularly to physics education. They share in common the fact that they are research articles written by researchers who have been specifically trained in science teaching. This means that they are not historians or philosophers making contributions from their own disciplines or physicists exploring history and philosophy topics. They are physics teachers and physics teaching researchers who, based on a solid background as regards the nature of science,

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[6] *Revista Ciencia Hoy.*

identify problems in physics teaching and learning and deal with them from a historically and epistemologically contextualized approach.

The following are examples of articles of such a kind (all of which were published in the 'Research' section, except one that appeared in the 'Thesis' section):

'Teachers' conceptions of the role of scientific models in physics classes' (Islas and Pesa 2004)
'The Scientific Revolution in the Argentinean Education System' (Cornejo 2005)
'Analysis of relevant aspects to deal with the Special Relativity Theory in the last years of secondary school from a historically and epistemologically contextualized approach. First part 1 and 2' (Arriassecq and Greca 2005)
'Laboratory work design within an epistemological and cognitive framework: Physics Teacher Training College case' (Andrés Zuñeda 2006-doctoral thesis-)
'Mechanics teaching at secondary school: historical evolution of the texts (1840–2000)' (Cornejo and Nuñez 2006)
'The view of a group of science teachers on science and schooling' (de la Fuente et al. 2006)
'Teaching the philosophical components and the different views on the world of science: some considerations' (Matthews 2009)
'Epistemology for physics teaching training courses: transpositive operations and the creation of a 'metascientific school activity'' (Adúriz-Bravo 2011)

71.4.4 *The Incorporation of Contributions Made by the HPS into Argentinean Textbooks*

There is research that studies how to incorporate the HPS into the physics textbooks used by both teachers and students. Arriassecq and Stipcich (2000) follow this line of scientific enquiry. Their work offers a critical analysis of the incorporation of the HPS into physics secondary textbooks that were written after the educational reform that took place in Argentina in 1993. One of the main conclusions these authors point out is that the HPS is not incorporated into school textbooks within a theoretical framework but it is rather reduced to mere anecdotal vignettes or, at best, to the inclusion of a chapter on epistemological aspects which do not bear any relationship with the rest of the text structure and approach. They also draw attention to the need to incorporate concrete proposals to deal with the contents of the HPS in class.

In later studies (Arriassecq and Greca 2004, 2007), it is argued that the results of different investigations point out that:

- The textbook appears to be the main resource that teachers use for preparing their classes, especially at secondary level. The same textbooks are recommended to students.
- The way in which topics are approached may seriously condition the results achieved by students when learning them.

In the same studies, which refer specifically to the treatment textbooks give to the special relativity theory (SRT), it is argued that the teachers who face the task of approaching the SRT for the first time will generally resort to the textbooks as a guide for their classes. Considering that in many cases the teacher has not had the opportunity to reflect on which concepts are the most relevant to understand the theory, he will probably follow the plan offered by the textbook or several textbooks he has selected to prepare his class, without adapting the material to fit his own criteria.

On the other hand, the results presented in this article coincide with those obtained on the same topic in other countries. This demonstrates that in order for secondary teachers to approach topics, such as the SRT in this case, from an epistemological and contextualized perspective, the available teaching materials are inefficient.

Based on that fact, it seems necessary to produce teaching material to be used by teachers and students, which provides for students' meaningful learning by introducing contents appropriately from a conceptual and motivational point of view.

This material could offer a serious discussion based on the contributions made by research into physics education, about the contextual aspects that are relevant to several physics theories.

Kragh's contextualized, or 'anti-Whig', approach analyses historical events in light of the beliefs, theories and methods that belong to the time when the ideas were conceived. This view offers a more realistic idea of history that does not fail to take into account obstacles and mistakes in scientific work. This view of science that textbooks may therefore reflect would be more realistic since it would give the same importance to successes as to failures.

71.5 Incorporation of HPS into Biology Education in Argentina

This section evaluates the incorporation of HPS into biology education in Argentina. The analysis focuses on the most relevant aspects of the curriculum for biology teacher training and research and the dissemination articles published in *Biologics Teaching Magazine*, which is a publication that has been issued by the *Argentinean Biologics Teachers Association* (ADBiA) for the last 15 years.

HPS has been incorporated into biological sciences and their teaching, both in the curriculum and in teacher training colleges, on the basis of complementary lines of development. On the one hand, there has been an advance and an epistemological turn in the development of knowledge in biology in the twentieth century (the molecular revolution, genetics and biotechnology, ecosystemic studies regarding human production, economy and consumption). On the other hand, the global/local crisis in scientific education has given birth to a second line that questions the science curricula, and a third line refers to science teaching in search of identity as a field of education research.

71.5.1 Evolution and Changes in Biology

Biology studies life and its organization in unifying principles of different levels of complexity: biosphere, ecosystem, population, individual, organism, organs, tissues, cells, macromolecules and biochemical level (biodiversity, taxonomy, Mendelian and population genetics, embryology, biology of the organism, molecular biology).

It is a mainly historical and evolutionary science, which develops explanatory models based on different research methods – comparative, systemic, hypothetical-deductive, genetic and historical ones – within structural, functional and behaviourist approaches (Ruiz and Ayala 1998; Barberá and Sendra 2011).

The conceptual and methodological development of biology differs from the research paradigm for physics, since life processes – self-regulation, unstable equilibrium and invariant and irreversible evolution – are informed by diachronic and synchronic perspectives, articulating internal and external interactions in an open system. On the other hand, its explanatory models are connected with various social and human practices (Giordan 1997; García 2006).

Advances resulting from technological research and applications to improve the quality of life, such as the digitalization of the genetic code and its molecular delimitation, led to numerous developments in biochemistry, medicine, technology and science. These, in turn, brought new and complex ethical problems with an economic and social impact (transplants, medicines, biochemical weapons, food production and biotechnology) (Testart and Godin 2002; Geymonat 2002).

With that in mind, and as a result of the multiple ethical conflicts, studies have been promoting new research and educational directions that combine new approaches (environmental, STSE, humanistic ones) with the bioecological, social, economic and political dimensions (Gudynas 2002; Sacks 1996). As a result, different areas of knowledge have produced proposals of an interdisciplinary nature linking science, cultural practices and the natural and social environment, as is the case for health and environmental education.

Biological knowledge in textbooks and curricula was not greatly updated until 15 years ago when the popular communication of the issues offered an opportunity to revise knowledge in interaction with health, economy, agricultural production, food and medicine industries, etc. (Datri 2006; Memorias ADBia 1993–2000).

71.5.2 Scientific Education Crisis

The international education movement following this line (Fourez 1997; Jenkins and Pell 2006; Hodson 2003), as well as the dissemination of magazines dealing with science education during the last 40 years, is evidence of the ideological turn which took place from the 1970s, affecting the objectives of scientific training. Some of them that centred on the development of theories and concepts pertaining only to the discipline were gradually modified by the incorporation of new objectives and strategies – the scientist's doings; the question of method and disciplines; and the incorporation of history, the sociocultural context of science and the ideological, economic and ethical assumptions (Latour and Woolgar 1995; Matthews 1991, 2009).

The science teacher associations, the AAAS and the NSTA (National Science Teachers Association, USA), have been contributing with their harsh criticism since the 1970s: they recommended in their documents of the years 1979 and 1986 that students should be given the chance to explore the history and the philosophy of science. In other words, students should reach basic understanding of how sciences and technologies were developed in the context of humanity. The long-standing recommendations and projects for the incorporation of HPS into science education constitute a tradition that dates back to the mid-nineteenth century (Paul Tannery, Pierre Duhem, Ernst Mach), the analysis of the historical cases of Harvard's project (Conant, James) or the British Nuffield project (Duschl 1995; Datri 2006; Martínez and Olivé 1997).

Therefore, the so-called science for all takes up the 1960s and 1980s challenge (Secondary Curriculum Review 1983 Great Britain; Learning in Science in New Zealand) to try to cover educational deficiencies that are the consequences of a scientific and cultural heritage from the mid-century: the break with the certainties of scientific progress and the manipulation of its intellectual product (Fensham 2002; Ramontet 1997). Such contributions lead to educational proposals based on three lines: 'Science in society', 'Science in a social context' and 'Science and Technology in Society', developing a range of topics that give rise to teaching booklets on scientific work: the role of government and industry in science, the commercialization of scientific breakthroughs, the involvement of researchers in food production, the fight against disease, nuclear weapons, technology in everyday life, etc.

These events interact with an educational crisis in biology teaching at school level which establishes the need for science for all, from the point of view of its role in society rather than science itself, thus adding weight to the arguments that claim that the curricula present a very limited vision of science, without any historical and cultural contextualization or any reference to its social impact. This approach aims to motivate the student not only to study scientific disciplines but also to view themselves as citizens and to be able to take a stand on the value and the use of scientific knowledge.

It is in this spirit that the *Argentinean Biologics Teachers Association* (ADBIa 1993) began active participation and played a crucial role in establishing and defining the epistemological scope of the contents set by the education reform in Argentina (1995, 1997) and in highlighting the need to include contextual, historical and ideological approaches in the biology curricula. After the return of democracy (1983), teachers' opinions on biology teaching became visible during the discussions within the framework of the curricular reforms, pointing out as weaknesses the dissociation between what is taught and real everyday problems, the encyclopedic approach, the atomization, the lack of the history of ideas and cross-cutting topics (ADBia 2002). In this respect, secondary teachers are the ones who have made constant demands for the updating of the subject in line with the results of research in the field of biology (De Longhi and Ferreyra 2002).

In the 1990s, the Science, Technology, Society and Environment (STSE) approach pervaded biology educational programmes in different ways: (a) CTS[7] was incorporated into a year or course; (b) from *scientific problems to concepts* was taught from the CTS approach; and (c) the scientific content in CTS proposals had 'a subordinate role' (Marco Stiefel 2005). It should be noted that the STSE approach was expressed in the biology curricula through the teaching of environmental conflicts, facilitating a break with the traditional scientific content and introducing new strategies for understanding and dealing with the environmental conflict, the study of the social reality and a conscientious citizenship.

Concurrently with the contributions from the new philosophy of science, psychogenetic studies on biological notions (Giordan and De Vecchi 1987; Piaget and Garcìa 1982), in 1990 the ADBiA Journal presented an interesting alternative to explore the historical perspectives of the ideas and the socio-cognitive processes in students, in this way providing the educational debate with new epistemological criteria for establishing the curricular science contents. In this context, it therefore became essential to reintroduce the history of science and its conceptualization, especially the two characterizations regarding the nature of science, expressed as (a) science as a process of justification of knowledge (what we know) and (b) science as a process of discovery of knowledge (how we know).

In this regard, the first characterization has dominated the contemporary teaching of biological sciences, providing incomplete knowledge of its conceptual and axiological field. There is at present a need to broaden the science curriculum and to design and implement teaching proposals that deal with the other aspect, that is to say, 'how' the model for the transmission of hereditary traits or its evolutionary process became known (Wolovelsky 2008). This involves going beyond a simple historical account as the central theme of our classes to deal with philosophical views which serve as tools for analysis and meta-reflection, allowing a better understanding of the aspects of scientific practice and showing the different lines of argument in the context of technological and sociocultural breakdown (e.g. the spontaneous generation theory of the twelfth century, the fixism theory in the sixteenth century or the synthetic theory of evolution in the twentieth century). There are many beliefs and pseudosciences present in our culture, especially regarding topics like the origin, continuity and evolution of life, to which the historical and philosophical contextualization may significantly contribute by favouring less radicalized and less dogmatic positions (Schuster 1999; Palma & Wolovelsky 2001).

In this regard, we now know that the meta-scientific approach allows the establishment of relationships between the knowledge taught and its historical and evolutionary context, problematizing it within a cultural moment, with the strategies, ideas and problem-solving approaches available at that time. This meta-scientific component in the definition of science teaching practices on the

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[7] Ciencia, Técnica y Sociedad.

one hand informs strategies for didactic transposition and, on the other, broadens the scope of traditional science teaching and learning models (Adúriz-Bravo et al. 2002b; Aduriz-Bravo 2005; Quintanilla et al. 2005).

Following from this, objectives have been set for the teaching of the biological sciences which relate to those skills students should develop:

- To learn the concepts within the context of the models and theories that created them. That is to say, bring the intention behind the phenomena closer to the models put forward by the scientific community. Such interpretation calls for the development of cognitive and scientific reasoning skills, usually referred to as 'doing sciences'.
- To promote conceptual change, practical and argumentative reasoning and understanding of the problematic, historical and cultural condition of scientific practice.
- To develop critical and projective thinking, which enables students to give opinions and take decisions. All of the aforementioned should provide for a non-neutral image of science under constant review, with technological applications and immersion in a sociocultural context.
- Promote, in turn, scientific literacy that provides basic culture and enables students to take decisions, analyse information, raise questions and detect deception.

71.5.3 The Identity of Teaching as a Research Area

On the one hand, the studies developed from the teaching of science provide an area of epistemological enquiry and revision of scientific knowledge, developing processes of transposition of communication and teaching hypotheses.

In this regard, the history and evolution of the major theories of the last 150 years confer identity to biology concerning not only its content and explanatory models but also the impact such knowledge causes, the attitudes it fosters and its relationship with different ways of life and culture (Memorias de las V Jornadas Nacionales de Enseñanza de la Biología). Instead of an academic practice, the teaching of science becomes therefore a learning process oriented to daily life, community, work and production activities.

There emerges the view that the student should acquire an idea of science connected with social issues, especially specific present ones. Among these, we can mention those related to the main pillars of development and sustainability, the management of natural resources, the oil and petrochemical industry, the mining industry and technologies, agriculture and agroindustries, metal mechanics, the food industry, the environment, health and biotechnology (Meira 2006).

Present societies are gradually becoming more and more dependent on technological knowledge, restating the relationship *production-information-education.* A new kind of citizen literacy is then suggested since the communication and appropriate significance of topics related to health, nutrition and pollution demand individuals who can be critical of problems and their solutions and able to improve the quality of life and their environment. In this direction, research into teaching has also proved that learning centred only around the incorporation of conceptual content fosters a distorted and limited view of scientific activity and its real production practices.

A wide range of research works agree on the fact that students gain a better conceptual understanding when they try to understand the origin and nature of knowledge, the argumentative conflicts and the sociology of research, as well as the ethical and attitudinal dilemmas among individuals and institutions (Jiménez and Sanmarti 1997; Lemke 2006; Rivarosa et al. 2011).

Moreover, the systematization of research into biology teaching at the national level (De Longhi et al. 2005; Berzal 2000; Astudillo et al. 2008) highlights the need for innovation in teaching practice based on issues related to (a) the history of biological notions and their epistemological development and the analysis of students' notions and conceptual obstacles and the problematic issues in connection with biology and culture, (b) the teacher's background and thinking and the transposition of communication and (c) the teaching models and the curricular materials.

It should be noted that the main concern in the last decade (2000–2012) has been mainly to promote curricular and training opportunities (postgraduate courses, master's degrees, seminars) for teachers to develop a real understanding of scientific activity and its relationship with genuine issues, to be used as a relevant criterion to rethink the teaching of biology. For this purpose, time should be devoted to education research into major biological notions, the analysis of documentary sources, biographical texts and historical events, the levels of curricular complexity as well as tracing back instances of scientific performance, all of which will help to question and change conceptions regarding biological theories and their teaching.

Furthermore, the bringing together of the meta-scientific knowledge (HPS) and the teacher's subject and teaching knowledge provides complementary options for problematizing themes. These allow for the combination of conceptual history and experimental design, theory and argumentation, metacognition and educational transposition and the relationship among science, culture and society.

In this regard, knowledge of the historical evolution of the issues that make up scientific culture provides a greater opportunity to 'devise' new strategies and educational objectives, the purpose and the reason for educating in science, that is to say, what is the importance of scientific education in our present society? Who is science for? What ideas and values underlie research practice? Does the available scientific and technological knowledge foster a way of thinking and acting for social change and the improvement of the quality of life and the environment?

71.6 Conclusion

The last 20 years has seen a significant rapprochement between the area of science education and HPS. Advocates of the incorporation of aspects of the HPS into science teaching, even though they are aware of the existence of differing opinions, stress the importance of a contextualized approach to this topic. That is to say, teaching science in a way that would allow students to carry out a critical analysis of the fact that the social, historical, philosophical, ethical and technological context is closely linked to the development, validation and application of scientific knowledge.

However, it is worth pointing out that, as Matthews (2000) states,

> It is unrealistic to expect students or preservice teachers to become competent historians, sociologists, or philosophers of science. We should have limited aims in introducing questions about the nature of science in the classroom: a more complex understanding of science, not a total or even a very complex, understanding.

Nevertheless, it is essential to consider in greater depth the reformulation of curricular projects at the different education levels – including science teacher colleges of education – taking into account the evaluation of the results obtained from them. At the same time, it should, on the one hand, be necessary to consider the possibility of training practicing teachers who as undergraduates never had the opportunity to approach the issue from this perspective. On the other hand, a greater production of written teaching material for students as well as for teachers should be beneficial. In recent years, there have been a growing number of research studies of science education that present teaching units for different science topics within a historical and epistemological context and that take account key aspects of the NOS. However, only a few of them transcend and reach teachers, pre-service teachers and students.

If one examines the aspects of NOS that have been incorporated into curricular designs during the last twenty years in Argentina, one notices a significant development. At the same time, research work in the subject has increased, and teachers are kept informed about the results of such research through national magazines, among others. However, it is necessary to promote other training instances for those in-service teachers who have no access to these publications or conferences. This is essential if it is our aim to form scientifically literate citizens.

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Part XIV
Biographical Studies

Chapter 72
Ernst Mach: A Genetic Introduction to His Educational Theory and Pedagogy

Hayo Siemsen

> *An effect size of d=1.0 should be regarded as large, blatantly obvious, and grossly perceptible difference.* Jacob Cohen (1988), "inventor" of the meta-analysis
>
> *[…] one gets large numbers when one weighs an elephant with gram weights.* An eminent statistician in defence of the dissertation of Wertheimer's assistant Luchins after one year of discussion about a possible error in it

72.1 Introduction and How to Read the Article

This article will attempt to provide a genetic introduction to the ideas of Ernst Mach, especially concerning education. It does not include a biographical overview on Mach as this can be found in many other sources (see end of the article). The first part of the article will give an introduction on how to read it (and why it is important to know). The next part will then provide an overview on the teaching phenomena associated with Machian teaching. These phenomena tend to be far away from most teachers experience with teaching. Even supporters of Mach often do not believe that such phenomena are possible. Therefore, the following part is concerned with the empirical evidence showing why the difference from an exponential teaching model to a standard linear teaching phenomena is so large ("[…] one gets large numbers when one weighs an elephant with gram weights", see Luchins 1993, p. 162). After that, the main idea of Mach is elaborated, i.e. why he changed from the antique understanding of genesis and adapted to a post-Darwinian concept of genesis. The main implications of this adaptation are then elaborated: sensualism,

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gestalt[1] (economy of thought) and *erkenntnis* theory.[2] Finally, Mach had several successors, whose teaching one can use as empirical examples of Mach's educational meta-method.

Understanding Mach's ideas is very challenging. This can be seen from the many, often contradictory attempts of eminent scientists to do so. Why is it so difficult? Mach integrates facts, phenomena and observations from many different sciences as well as pre-scientific ideas. His goal is to provide *general* concepts, applicable for and consistent with the knowledge from all sciences and all experience. They are thought economical, i.e. one concept can be applied to many or – if possible – all fields of knowledge.

In order to achieve this, Mach takes a fundamentally different world view. As he emphasises, this is not a necessary view. Other views are possible. Like one can see the movement of the solar system and the stars from earth in a geocentric, Ptolemaic view, or one can view it (as a fictional thought experiment) from the sun, a Copernican heliocentric view. For Mach the difference is mostly an economic one. Each view serves as a yardstick, a "currency" by which concepts are "exchanged", i.e. related to each other. For some measures, one view will be the more economical, e.g. practical; for other purposes, another view might be more central. The sun – because of its high gravity – influences the other planets much more than they influence each other, except for those close to each other, like the moons to their respective planets. Therefore, the movements of all planets are easier to understand from a heliocentric view than from a geocentric one. But for the observation of the moon relative to the earth (e.g. for sending a rocket to the moon), a geocentric point of view is often the easier, more pragmatic point of view. Flying over the Atlantic, one rarely bothers to imagine or even calculate the distance via the sun (*Helios*). Likewise, Newtonian physics is mostly sufficient for such a flight, though maybe not anymore for moon or space travel.

Points of view thereby serve as "currencies of exchange" between concepts. They provide a single theoretical point, through which one can compare the relations of many or all observations, just as one can value all kinds of goods via one currency. Without a currency, i.e. in a barter economy, one has to remember how many oxen have the value of a horse and how many sheep have the value of two horses as well as how many sheep one can trade for an ox. If one now imagines that there are not only oxen, sheep and horses but also different qualities of cloth of different width to trade with the service of bringing the oxen to my farm passed the raiders on the road, etc., the value of a standard currency for the economy of memory and calculation becomes obvious.

Such a currency of course is most valuable, if one can use it very broadly. The Euro and US dollar have their respective "usage" value not only because of some gold reserves but also because they are used in many places by many people. Applying this

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[1] For Goethe a *gestalt* used to be a "whole". Mach changed this into a genetic understanding of the concept, where a gestalt is like a species. It can adapt and transform; it is a process and a product (plasticity). Why it is thought economical will be explained later.

[2] *Erkenntnistheorie* in German means something in-between theory of knowledge, cognition and epistemology, though it is neither of these.

analogy to making concepts comparable over many disciplines, Mach's world view is optimised to represent the most economical view.[3] Mach's world view consistently comprises most known facts from all different areas of human experience. Experiences from different domains can thereby not only be compared but also be used complementary; reciprocally, they can "inform" each other. The relation between concepts is always possible via the currency. The basic concepts forming the world view are explicit as far as possible, including pre-scientific, intuitive concepts. If one does not do this, like in many speculative theories, a single mistake or inconsistency in the beginning can metastasise manifold and – as in the case of the Euro in 2012 – come back to haunt the founders much later.

A singular view furthermore generalises many concepts so that few concepts can stand for many facts. One idea, once thought, just needs to be reproduced from memory and applied everywhere. This application is not just analogous, but is based on the most general facts and experiences. Like the Euro, it requires a larger investment in the beginning, because many existing currencies need to be replaced and – also like the Euro – it as well requires "political" (philosophical) adaptations of many pet ideas held dear.[4]

In what way is the psychophysical[5] world view which Mach proposes more consistent than other views? The view comprises the physical view (about the world) and the psychical view (about ourselves and how we individually experience the world) into a singular meta-perspective. This singular general perspective is called monistic.[6] In order to be able to say something about the world, one needs to have a physical theory. This theory is first of all a private theory. It might – depending if and how much one studied physics – be naive or more sophisticated. Sophistication here only denotes how much the theory will cover regarding potential experiences. Will it still work when applied to a double-slit experiment? Will it still apply to the workings of CERN? Few people in the world will have developed their physical theory to the latter. If the physics of tomorrow is different from today's, such a view might also then become quickly outdated.

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[3] This is why Mach acknowledges that there are several world views possible, but others are optimised for other criteria. It would of course be scientific to always make these criteria explicit so that one can compare the motives.

[4] This often causes – sometimes very sudden and fierce – emotional rejection of the ideas. One feels like the previously sturdy floor on which one learnt to walk is suddenly pulled away underneath one's feet. Siemsen et al. (2012) call it the "rug of horror" symptom, describing the emotional trouble of some students facing up to some of their lifelong inconsistencies in learning. The mathematician Weyl (1928) put it in a different metaphor when the sturdy mathematician's "tower of knowledge" is "turned to mist". Kurki-Suonio recalls that the in-service teachers he taught always showed one year (in a two-year course) of "resistance" before a gestalt switch in their world view (for the technical details how the course was implemented, see Lavonen et al. 2004). The older one gets, the more one tends to become emotionally attached to often used habits of thought.

[5] Mach's generalised interpretation of psychophysics as a world view is unusual, also in psychophysics.

[6] This is not necessarily contradictory to what William James called a "pluralistic world view", because Mach's view deliberately comprises different perspectives. Mach makes them comparable, without claiming absoluteness, just economy.

On the other hand, as humans we also require a psychical view. Otherwise we cannot conceptualise other humans (and ourselves as different from them). Such a "theory" in its rudiments is formed in very early childhood (when the child starts to communicate and interact with its fellow human beings).[7] Later, this "naive" theory might become more sophisticated through systematic psychological observation and experimentation, i.e. by a "scientific" psychical theory.[8]

What Mach now proposes is to combine the physical and the psychical view[9] into a singular world view (general or meta-perspective). Although such a singular view is again very close to the initial perspective of a baby, we could not have acquired it without having previously gone through many human experiences. This view is an abstraction derived from these experiences.

One needs to shift one's view away from a mainly dualistic view in which one sees the "world" and the "self" as separate entities, towards a monistic view. In a Machian monism, one assumes the relations between the "world" and the "self" as the basic elements. One can only know that there is such a relation. What one learned to know as the "world" and the "self" are then only intuitive constructs of such relations from childhood.[10] In order to know, what the relation is, one has to apply the physical view and the psychical view, like standing on and walking with the left as well as the right leg.[11]

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[7] Thereby, Mach's psychical theory is first of all a theory of the individual, not of the "self". The "self" in his view is just one outcome, a construct of individual (sensual) experiences.

[8] The process of science for Mach consists in a higher economising by systematically using and testing the experience of many people and making them comparable though a more standardised framework of observation.

[9] For this, one should take more sophisticated and consistent versions of these views in order to consistently cover many facts and human experiences.

[10] "Every human discovers within himself, when waking up to his complete consciousness, already a completed image of the world, to which accomplishment he did not at all willingly contribute to and which he accepts on the contrary as a gift from nature and of the civilization and as something immediately intelligible. This image was built up under the pressure of the practical life; extremely valuable, in this regard, it is inerasable and never ceases to act upon us, no matter which are the philosophical views that we will later adopt". "Here everyone has to start" (Mach 1905, p. 5).

[11] "For most natural scientists and many philosophers, who do not admit it, the thought that all psychical could be deducible to the material is very congenial in private. Even if this materialism has a catch, it is not the worst possibility; it stands at least with one foot on secure ground. But if all psychical should be understandable physically, why not the other way round? […] Is the other [psychical] foot standing in the air? I would prefer […] to stand on both feet. […] There is no necessity to become dualist thereby for the one, who considers both feet as equal and both floor spaces under the soles to belong not to two different worlds" (Mach 1920, p. 434; 1883/1933/1976; 1883/1893/1915). In his book *Knowledge and Error* (1905), Mach uses such a dual approach, switching back and forth between a physical and a psychical perspective. This (and other unusual features) seem to have been unfortunately too much for instance for the translators (in English as well as in French) to cope with. Especially the translations of his books have led to many unfortunate misunderstandings of Mach's ideas (except for the excellent translation of *The Mechanics* by McCormack and Pierce, though that has suffered as Jourdain complained from not being updated to the many further developments Mach included in the later German editions).

Mach calls this relation "sensory element". He states that he could interchangeably call it "physical element", though then people would easily mistake it for physicalism. The relation is very broadly defined, including the sun lighting the perceived object as well as the memory (and prior experience), which makes the object recognisable. These psychophysical relations thus have a genesis, which needs to be researched. What one perceives as simple relation might actually under scrutiny turn out to be a cluster of relations. The sensual elements are therefore recursively defined. Although the relation is "immediately given" as a gestalt, this perceived "immediately given" represents only one side of the relation. The "given" is not simple, but requires many perspectives of research of which none can ever supposed to be final. Even the habitual separation of sense elements into senses might already be too much reductionist or too little. One cannot know a priori, one can know only genetically. Sensual elements are gestalts, i.e. they adapt and transform like species.

Other monisms of course exist, namely, physical monism (materialism or physicalism), which presumes that all psychical phenomena are epiphenomena, and the "panpsychism", which supposes that everything is initially psychical. There are also more or less arbitrary combinations of the two, delimiting the rule of one relative to the other (James noted that some monisms are actually dualisms under disguise). Finally, there are the "parallelisms", which suppose that the physical and the psychical always go together "in parallel", like a tandem. But as one might notice, Mach's feet will rarely work "in tandem", i.e. hopping together, but rather complementing each other while walking (Mach used the metaphor of a "tunnelling" between the two perspectives, i.e. a process, which brings them continuously closer together). Mach's psychophysical relation is only the starting point of genetic (and other) enquiry.

The "problem" of this shift in world view is one of learning in general. As one learns a different way of learning, one has to discard previous ways of learning or at least to adapt them to the new framework. Learning methods tend to be well associated (neurally connected), because of the high frequency of learning in general. Changing these associations is more difficult than regular learning. It is not only learning something new but resembles changing early childhood experiences, like sometimes done in psychotherapy. There are hints that such meta-learning involves not only changes in neuronal connections but also actual formation of new neurons on a scale not regularly observable in learning processes (see, e.g. Buonomano & Merzenich 1998).

The view presented here is not a standard (formal) account of Mach's ideas. It is a genetic introduction to Mach's ideas. New concepts will be introduced genetically, i.e. starting with a more standard meaning and then successively being transformed into Mach's usage. As several of the main concepts, such as *erkenntnis* theory, genesis and world view, are reciprocal, i.e. have to be developed interdependently, they need to be introduced before each concept is fully developed in its new meaning. One thereby has to read the text several times. The first time, the footnotes can be left out. In the second reading, they provide additional facts and information for further transforming some important main concepts. In a third reading, one can therefore focus mainly on the footnotes and skip through the main text. If possible, one should also leave a night in-between these readings. On the next day, one will be able to identify the less well-understood parts more clearly.

72.2 The Phenomenon of Genetic-Adaptive Learning

William James called the lecture he heard from Mach "one of the most artistic lectures I ever heard" (Thiele 1978, p. 169).[12] What constitutes this artisanship of teaching? James (Thiele 1978, pp. 169/173) later tried to copy this method as well as Mach's world view in teaching his students: "I am now trying to build up before my students a sort of elementary description of the construction of the world as built up of 'pure experiences' related to each other in various ways, which are also definite experiences in their turn. "There is no logical difficulty in such a description to my mind, but the *genetic* questions concerning it are hard to answer." I wish you could hear how frequently your name gets mentioned, and your books referred to". James thereby encounters some effects of genetic teaching, which – when compared to other cases of Machian teaching – seem to be typical, including the difficulty of implementing the genetic questions (as Mach had noted – see later quotation – this can be as challenging as finding the idea in the first place). What are the typical effects of genetic-adaptive learning?

Intensive (transformative) experience: There are accounts of people who have been influenced by Mach and genetic-adaptive learning by just two hours (Siemsen 1981), an oral exam (Heinrich Gomperz), even of 10 min (in the case of Karel Lepka[13]) or hearing one lecture from Mach (Fritz Mauthner, one of the founders of linguistic critique, see Siemsen 2010a). This short time was sometimes enough to change the lives of the people involved (for instance, when Karl Hayo Siemsen met Joachim Thiele[14] once for two hours, but now considers himself following in his footsteps). Also people who have been influenced by Mach, such as Schumpeter, are known to produce this effect.[15]

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[12] Mach's way of learning will in the following be called "genetic adaptive". Such learning should be viewed like a Darwinian species: a process and a product. The growth processes are exponential rather than linear; they adapt and transform. Therefore, some empirical results from such learning might look extreme and unbelievable to anybody who has never observed them. Nevertheless, over the last 150 years, there have been many such empirical observations in many contexts, mostly influenced directly or indirectly by Mach.

[13] Lepka is professor for mathematics education at Masaryk University, Brno, CZ. He described this occurrence in detail in several interviews 2011/2012. Several other students of ernohorský have described similar, though a bit less extreme effects.

[14] Thiele first systematically published Mach's letters. From this work he gained important insights on Mach missed by many other Machian scholars.

[15] This effect and several of the following effects can certainly be observed in other circumstances, which have no Machian background. Nevertheless, some of the following effects are unique. Others are unique in their combination, frequency of occurrence or reproducibility. In all known

Inspiring eminent new ideas in multiple areas: In principle, this seems to be a corollary of the transformative experience described before (though in many cases, it has not been properly described). Few people have influenced so many eminent other people than Mach. Maybe the last time this has happened in human history were the many schools of thought founded after Socrates (and maybe the many ideas Galileo inspired; though in that case it is difficult to trace this effect mainly to Galileo). Mach has directly or indirectly influenced not only a handful but also many Nobel Laureates, even much after his time and not just from one area, but all areas in which such prizes are awarded.[16] Einstein (1916, p. 102) provides a metaphor for this type of intuitive influence. Regarding his own generation of physicists, "I think that even those who think of themselves as enemies of Mach, don't remember how much of Mach's approach they have – so to speak – imbibed with their mother's milk".

Aspects of this "mother's milk effect" can be found in several areas, methodology, epistemology, praxis, etc. For instance, according to Einstein (1916, p. 102/103), it "trained [the physicists] to analyze the long-time prevalent concepts and to show, of which circumstances their eligibility and usefulness depends upon, how they have grown in detail out of the conditions of experience. Thereby, their excessive authority is broken".

The mother's milk did not start with Mach's famous *Mechanics*. There was a genetically even earlier mother's milk for many eminent scientists in German-speaking countries. The effect was transmitted through Mach's schoolbooks, which they grew up with (and certainly could not remember consciously) between 1886 and 1919.[17] They already learnt the concepts the Machian way. Even though some, like Planck, later criticised aspects of Machian ideas, they still intuitively retained and used nearly all of his *erkenntnis* theory (see Siemsen 2010c).

This did not only happen in physics but also in chemistry (where, for instance, Wilhelm Ostwald was close friend and admirer of Mach) and biology. Especially in medicine, Mach's teaching of "physics for medical students" in his *Compendium* (Mach 1863) had long-term effects, as many medical students were travelling all over Europe during their study times. As other eminent scholars – even such as the likes of Wundt – did not have a consistent *erkenntnis* theory of their own (as James had noted), the students coming out of their labs were mainly Machians, at least in their *erkenntnis* theory (such as Kuelpe or Titchener, see Boring 1950/1957).

Machian teaching phenomena, several of the effects have been observed, while other effects might have been overlooked as the effects have never been systematised.

[16] For example, Einstein, Pauli, Bohr, Planck, von Laue, Raman, Heisenberg, Rabi, Bridgman, Ostwald, Arrhenius, de Broglie, Landau, Ramsey, Polanyi, Wilczek, Eigen, Lorenz, Musil, Bergson, Hayek, Samuelson, Simon and Coase. No systematic inquiry has yet been made on many others. Especially, it would be interesting to know how many winners of the "physiology or medicine" prize have been in Mach's "physics for medical students" lecture. Probably there are several. Mach himself was suggested for the prize but probably was too much of a generalist for a specific prize. There is no Nobel prize for *erkenntnis* theory.

[17] See Siemsen (2012a) or Hohenester (1988).

Also many eminent economists, such as Schumpeter, Hayek, Georgescu-Roegen, Samuelson and Polanyi, took a deep zip of Machian mother's milk. Even many artists were not free from this influence. Some, like Schnitzler or Hofmannsthal, had even been attending Mach's last lectures in Vienna, while the literature Nobel Laureate Musil wrote his dissertation on Mach. There were also influences on linguists (Mautner), philosophers (Wittgenstein, Feyerabend, Popper, Vaihinger, Radulescu-Motru), sociologists (Zilsel, Cohen, Neurath), mathematicians (Poincaré, Nevanlinna, Haret, Hadamard, Hahn, Menger, Weyl, Brouwer, Mandelbrot, Marcus and 65 recent mathematicians and maths teachers, see Ahlfors et al. 1962), historians (Sarton, Koselleck), anthropologists (Boas, Lowie, Malinowski and through their students also Jerome Bruner), biologists (Loeb), logicians (Pierce), philosophers of science (Frank), etc. (see Holton 1992; Siemsen 2010a, d).

Why has Mach's central role in these general aspects often not been properly described or even recognised? Einstein gives a hint when he tells his friend Besso in 1948 (Speziali 1972, Doc. 153), "Now, as far as Mach's influence on my development is concerned, it was certainly great. [. . .] How far [Mach's writings] influenced my own work is, to be honest, not clear to me. In so far as I can be aware, the immediate influence of D. Hume on me was greater. [. . .] However, as I said, I am not in a position to analyze what is anchored in unconscious thought".

Teaching is mostly intuitive: As Einstein had so aptly described with his "mother's milk" metaphor, much of Mach's teaching "becomes anchored" on the intuitive (nonconscious) level. This is a corollary of the intensive sensualism involved. The sensual relations belong to some of the oldest biological setup and are therefore mainly connected with consciously not easily accessible parts of thinking. To make them accessible to reflection is a task of *erkenntnis* psychology, which is unfortunately the least understood and reproduced element of Machian teaching. Kurt Lewin aptly called the result "practical theory".

When Mach's *erkenntnis* theory is acquired early, the transformative effects are not experienced as special. One might only later be surprised that other people's thinking is not the same. What is "normal" and therefore not special about teaching in Finland may be unique in the world. When asked what is special in their teaching, Finnish teachers are often not able to answer this question, or the theory provided might have little correlation with the actual phenomenon. Scientists (influenced by Mach) might intuitively know what to do and what works. When one follows their (later constructed) theory, one unfortunately cannot reproduce their results. What works for them works because of effects not covered by their theory (cases of this are, for instance, Piaget or Wagenschein, see Siemsen 2010b, 2012b).

Teaching becomes mostly independent of age and "stages": One of the theoretical (metaphysical) elements Piaget popularised in science education is the model of the "stages" of development taken from the intelligence scale of Alfred Binet. The stages are teleological, i.e. depend on a specific definition of culture and intelligence. They are not genetic. Mach instead describes the genetic process of popularisation:

> Once a part of science belongs to the literature, a second task remains, which is to popularize it, if possible. This second task also has its importance, but it is a difficult one. It has its importance, because – regardless of the distribution of knowledge that increases its value – it

> is not unimportant either for the further development of science itself how much knowledge has been disseminated into the public. The difficulty is to know the soil very well in which one wants to plant the knowledge.
>
> It is a prevalent but wrong opinion that children are not able to form sharp concepts and come to the right conclusions. The child is often more sensible than the teacher. The child is very well able to comprehend, if one does not offer too much new at a time, but properly connects the new to the old. The adult is a child when facing the completely new. Even the scholar is a child when confronted with a foreign subject. The child is a child everywhere, as everything is new to him. The art of popularization lies in avoiding too much of the new at one time.[18] (Mach 1866, p. 2–3)

Can this be observed empirically? For example, the physics Nobel Prize winner Wolfgang Pauli was godchild of Mach (born Pascheles, the family, especially the father, were close friends of Mach). He received *The Mechanics* (Mach 1883) as a gift from Mach when he was 8 years old. Another example is Peter Drucker, an eminent management "guru", who describes in his autobiography, how his 1 year of school in fourth grade in the Schwarzwald School[19] changed his life (Drucker 1979, pp. 62). He later adapted and used the methods he learnt in this year in school to management (see Eschenbach 2010).[20] They became some of the most influential ideas in modern management.

"*Bad" students suddenly become "good" or "very good"*: The "shift" of students improving in grades is not only by one to three grades (on a 5–1 or 0–6 scale), but can happen in "jumps". In many instances, for example, in Finland, but also for Siemsen et al. (2012) or Gabriel Szász,[21] initial "laggards" suddenly become excellent students. They thrive with the new method.

Alfred Binet, the "inventor" of the intelligence test and the concept of age-related "stages", which was later perfected by his student Piaget, late in his life worked specifically on the "laggards", i.e. the lowest 5–10 % on his intelligence scale. After a discussion with Mach, whom he had invited to write an article for his "*L'Anneé*

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[18] Instead of age groups and stages, the pre-knowledge ("not too much new at a time") becomes a more important factor. Some pre-knowledge might be enabling, some obscuring for the new *erkenntnis* process.

[19] One of the schools inspired by Mach.

[20] Another example is a girl of 3 1/2. She was supposed to learn about opera. After intensively using first very simple versions of the "Magic Flute" by Mozart (abridged puppet and children's versions), connecting these to previous experiences and repeating scenes as requested by the child, it became possible to watch a regular version of the Magic Flute. Now the question was if one could directly present her a "difficult" opera. One of the most challenging operas is certainly Wagner's "Ring des Nibelungen" (at least concerning the length and the complexity of the story, though also the music is challenging compared to Mozart). She loved it and though she was allowed to watch only smaller parts of the total 16 h at once, she always wanted to continue and remembered the scene where she had to stop before. Also she developed favourite scenes to be repeated and started to recognise gestalts from the opera in daily life. What was new for her was the medium of opera. Once she knew the basis of it very well, expanding (exponentially) from this basis was not a problem, neither of learning, nor of age.

[21] In courses on astrophysics at the Masaryk University in Brno, Czech Republic, 2008 and 2010 (see http://astro.physics.muni.cz/iwssp2008/ and http://astro.physics.muni.cz/iwssp2010/, accessed 25/08/2012).

Psychologique" (see Siemsen 2010b), Binet developed the concept of "mental orthopaedics" (*orthopedie mentale*) specifically for this problem. Mental orthopaedics is an application of psychophysics to learning. Unfortunately, Binet died shortly after implementing this idea for a larger number of students, but the rector of the school with whom Binet worked published some empirical results posthumously (Vaney 1911). The results show not only a very fast relative but also an absolute "catching up" of most students compared with the regular students (the school got the students only after a minimum of 3 years of "lagging behind" in a regular school, but many of them were on the same level after 2 years of mental orthopaedics). Additionally, although the singular "curves" seem to be linear, taken together they show a clear exponential component in learning.[22]

The phenomenon of the thriving students also shows that empirically, the so-called Matthew effect in education,[23] i.e. that good students tend to get always better and laggards continuously lose out on them, is actually not a fact, but an artefact of a linear learning paradigm.

Learning happens without outside pressure: The students themselves perceive this way of learning mostly positive (in spite of the previously described "rug of horror" effects), because there is no external pressure necessary for learning. The pressure and motivation becomes intrinsic, i.e. self-organised (see Siemsen et al. 2012). As a result, also motivation is not a problem anymore. All students want to learn, and the problem is mostly to limit the time for learning so that they have enough time for intuitively digesting what they have learnt while doing other recreational activity. Some adaptation of the thoughts to each other needs to take place overnight during sleep.

Time perception changes in learning: One indirect consequence of genetic-adaptive learning is the relativity of time perception in learning. Because the learning process

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[22] The details will be elaborated in a separate article following more detailed research. Karl Hayo Siemsen stated in a personal message that Binet basically used the same method as he used (Siemsen 1981), but 60 years earlier. Just that Binet used school instead of university students, but with very similar empirical results (Vaney 1911). This finding would imply that Mach, James and Binet, the eminent researchers in the German-speaking countries, the USA and France at the time, were all using in principle the same method as ideal teaching method. It seems unfortunate that the method got lost nevertheless, probably because James and Binet developed it only at the end of their lives, with the chaos of the world wars ensuing shortly afterwards. Thereby, the method was never even properly identified as a specific method with specific phenomena.

[23] The "Matthew effect" was first coined by Robert K. Merton in order to describe, for instance, that eminent scientists tend to get more credited for the same work than unknown ones. "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken even that which he hath" (Matthew 25:29, King James Version). This idea was then applied to education by Keith Stanovich regarding reading literacy. But the actual story is probably more intricate. A little bit before, Matthew also entails a "counter-Matthew effect": "But many that are first shall be last; and the last shall be first" (Matthew 19:30, similar in 20:16, King James Version). Maybe one should rename the effect in education instead into "Hit-The-Luke" (translation of "*Hau-den-Lukas*", the German name for a "Ring-The-Bell" at funfairs) for all the students who are never taught to become very good students.

is so intensive, the thoughts related to the learning process become dominant versus other background thought processes, such as the one keeping time.[24]

Learning takes place in genetic "loops": Genetically, many ideas and concepts cannot be introduced at once, but need repeated scaffolding and auxiliary concepts in order to develop. In such "groping phases" (Kurki-Suonio 2011), sometimes little seems to happen on the surface, while "suddenly" gestalt switches of whole ranges of concepts appear. This effect has also been described by Poincaré (1908) for how he found new mathematical functions for which he became famous. Contrary to common belief, such intuitive thought processes can be observed, measured and consistently reproduced (see Siemsen 1981, 2010a; Siemsen et al. 2012).

Genetic "loops" have been used by Mach already in his schoolbooks, but they become imperative for meta-learning as Mach describes: "The value of such general methods lies in the economization of thinking about the single case, in the easy templating of it. This cannot be understood, unless initially a whole host of single cases has been sufficiently dealt with through the consideration of very different details. More general methods in science are a result of much detail work and have to be this also in teaching. Without this, method is an un-comprehended gift. In the method lies the insight that one can think a thought one-and-for-all and does not have to think it again in each case. […] 'What you have inherited from your forefathers, gain it in order to own it'" (Mach 1876, p. 13).

Long-term and transfer effects: From the observations by Kurki-Suonio, Siemsen and ernohorský, but also from the Schwarzwald School (see, for instance, Siemsen et al. 2012), a student only has to pass through a teacher with genetic learning one time during his life and can afterwards apply the genetic learning as meta-learning on all other learning throughout his or her life. Siemsen et al. (2012), for instance, have shown strong transfer effects, where the *erkenntnis* theory taught in a project study reduced the percentage of students not passing a mathematics exam from 90 % to 40 % without any teaching of the contents of "higher mathematics 1" or the mathematics teaching being a core topic in the project study. The empirical results of the experiment of Siemsen from 1981 suggest that with some genetic mathematics teaching (2–4 h), this with 40 % still high dropout rate can be brought down to nil. Similarly, the long-term effect of genetic-adaptive teaching seems to show in terms of personality development. This is documented for many cases of the Schwarzwald School as well as students of ernohorský and Siemsen. Surprisingly many of them become professors, entrepreneurs, eminent writers, politicians (ministers and prime ministers), etc. When interviewed, they tend to agree that this teaching has had a very important effect on their career.

Exponential learning: If one compares the empirical effects of methods based on linear models of learning, one typically arrives at meta-analysis effect sizes of d between 0.0 and 0.6, sometimes up to 0.8 (see Hattie 2009).[25] Jacob Cohen (1988),

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[24] This effect is, for instance, also described by Csikszentmihalyi (1990) with his concept of "flow".

[25] Hattie (2009, 2012) comprises more than 60,000 empirical analyses on student achievement from more than 900 meta-analyses onto one scale of comparison, which is the effect size (after-before or

the "inventor" of the meta-analysis, argued that an effect size of $d=1.0$ should be regarded as "large, blatantly obvious, and grossly perceptible difference" (quoted by Hattie 2009, p. 8). This is as perceivable as more than 20 cm difference in the height of persons. Finland as a field experiment (OECD Pisa 2006) has a $d=1.0$. The problem can be that many teachers have never observed effects even close to this and therefore may regard such effects as "unbelievable",[26] contrary to Cohen's view.[27]

72.3 Empirical Observations When Changing to Machian Teaching

What happens if one changes to a Machian teaching? As Mach (1886/1893/1986) described, "I know of nothing more terrible than the poor creatures who have learned too much. Instead of that sound powerful judgement which would probably have grown up if they had learned nothing, their thoughts creep timidly and hypnotically after words, principles and formulae, constantly by the same paths. What they have acquired is a spider's web of thoughts too weak to furnish sure supports, but complicated enough to confuse".

Mach sees teaching very empirically. Today, most teachers experience that they have to teach too much in too little time. But this is an empirical illusion created by the standard (linear) teaching model. Martin Wagenschein (1970) suggested a simple empirical test against this misconception. How much knowledge is really taught, i.e. how much "remains" in long-term memory? Everything that is forgotten is obviously superfluous to teach in the first place. One can just repeat the test one does at the end of the course and repeat the same test 2 weeks after without telling the students beforehand. Repeat the same test after a year. How much of the apparent knowledge remains? On average it is just about 5–10 % (even if it would be

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experimental-control group divided by standard deviation). Meta-meta-analyses also provide an interesting opportunity for conceptual analysis and finding inconsistencies in the empirical meaning of concepts. If the results of different meta-analyses for one concept vary largely, this might be because the description of the concept or the concept itself is inconsistent or confused, leading the studies about it into different interpretations or into white noise.

[26] For an example, see Luchins (1993), the assistant of Wertheimer in the USA, recalling the problems with his dissertation about rigidity, which seemingly included exponential effects. This is an important reason to make statistical analysis of Mach's teaching method, because it grossly violates the gut feelings (intuitions) of many experienced educators. People with less experience have less trouble accepting it. The problem also effects student's evaluations of this method, because also their intuitive model of learning is linear, which leads to conceptual inconsistencies when confronted with exponential learning effects (see Siemsen et al. 2012).

[27] This "unbelievability" also happens in the method of meta-analysis. Typically the "outliers", i.e. the most extreme effects, are sorted out. Unfortunately thereby, if any Machian teaching effect was ever initially included in such a study, it will probably not have been further researched as best practice, but statistically eliminated.

50 %, still half the teaching is a waste of time).[28] So from an empirical standpoint, one should teach only the knowledge which is later present in memory and use the rest of the time of the course otherwise. The 95 % which is forgotten is a waste of time anyway, of the teacher and of the students. This is how one can teach more within less time.

This "watering down" effect of knowledge taught to (less) knowledge used is actually taking place severalfold throughout the education process. According to inquiries (by Mueller-Fohrbrodt et al. 1978), teachers tend to run into a "shock" of praxis after their theoretical education at university. They adapt mostly by throwing away what they learnt at university (see Mueller-Fohrbrodt et al. 1978). Teacher education has little effect on student performance (d=0.11, see Hattie 2009, p. 110). Professional development might still have a high effect on teacher knowledge (d=0.90 probably measured for short-term and not long-term memory and effects), but this is less implemented (d=0.60) and has even less influence on student learning (d=0.37, probably also short term, see Hattie 2009, p. 120). The experience of Kurki-Suonio (2011) in his in-service teacher training courses are that the Machian world view is more difficult to teach to teachers in the first place (high initial resistance/rigidity), but then the new gestalt is much more stable. It also leads to much higher student learning (d=1 long term for all of Finnish students with only 1/3 of Finnish science teachers trained in this way, see OECD 2007 and Siemsen 2011).

Mach describes the role of the teacher relative to the subject matter: "If now the teacher, who can present to himself the whole subject matter, subsumes a theorem adapting it to his *own* conceptualizations and to his *own* satisfaction of needs, then therein lies, if it happens unconsciously, certainly an error in the person whose satisfaction of needs is central in this case. If it happens on purpose, it is a didactical insincerity. For the student, premature completeness and logical finesse is useless and without any value, often even detrimental" (Mach 1890, p. 2/3). Why are 95 % of teaching used for teaching short-term memory? For the satisfaction and exculpation of the teacher, so that he or she can claim to have "taught everything"?

Empirically speaking, most of lecturing at schools and universities is wasted. Instead, one could free time for effective learning in the way described above and reduce overall time spent at school and university. In logistics, this radical approach of quality improvement is now standard. Quality management is not mainly about certification and formalising processes.[29] It is about reducing (or rather preventing) faulty products and processes.[30] In education, one could say that many products pass

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[28] One could call this test "Wagenschein's razor".

[29] "[…] control charts are justified for only a small minority of the quality characteristics" (Juran 1951, p. 308).

[30] Joseph M. Juran (1951, p. 247), one of the early "gurus" of quality management, wrote about "the principle of prevention" that "It needs no argument to conclude that it is better to prevent defects from happening than to sort them out after they have happened. Shop supervisors and personnel are fully aware of this principle. The failure to apply the principle of prevention lies *not* in any disbelief in the principle. Rather the problem is one of *how to achieve* prevention. Any lack of achievement is in turn not the result of deliberate (or even unwitting) resistance by individuals; it is rather the result of the limitations of modern industrial organization". Juran (1951, p. 248) then

the final quality test, but still more than 90 % fail in their first application.[31] This is a huge waste.

Japanese quality improvement calls instead for the identification and reduction of "*muda*", the Japanese word for waste (see Ohno 1978/1988, p. 18).[32] Taiichi Ohno, the Toyota engineer who made the Toyota Production System (TPS or Lean Management) popular, described the success of Toyota through the reduction of three types of waste: *muri* (overburden, beyond power, by force), *mura* (inconsistency, irregularity) and *muda* (waste).[33] Applied to education it would mean that one needs to cut all learning, which (a) has to be forced on the learner, which (b) is too difficult to learn in a singular effort or which (c) entangles and confuses the students rather than enlightening them. One further has to cut all inconsistencies in

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quotes Howell B. May (1921): "While inspection of the product is of much assistance in improving the processes, nevertheless its greatest usefulness is found in the prevention of loss from defective goods. [. . .] The success of inspection in decreasing the quantity of defective goods is based upon the fact that to maintain the necessary standards of excellence with minimum loss, the quality of the product must be known at all times". Inspection nevertheless should not be mistaken for exams and exams not with facts. "In a production plant operation, data are highly regarded - but I consider facts to be even more important" (Ohno 1978/1988, p. 18).

For achieving the compliance of students in the process, being open about not understanding something, the barrier between "work" and "fun" has to be broken down (Juran 1951, p. 269): "To the extent that a management can minimize compulsion, give impersonal supervision, allow participation in establishing objectives, provide creativeness, provide a social atmosphere, give meaning to what is being done, and provide incentives over and above money [. . .] it secures the enthusiasm as well as the compliance of the operator". It thus does not help to give bad grades for not understanding or to use grades for motivation.

[31] T. H. Huxley (1864/1870) warned in his inaugural speech as Rector of the University of Aberdeen that "examination, like fire is a good servant, but a bad master". A constant effort of passing exams has a deteriorating methodological effect on students: "They work to pass, not to know; and outraged science takes her revenge. They do pass, and they don't know". The worst is that students also do not care that they forget more than 90 % shortly after the exam. They should be the first to complain if they do not learn as it is a loss for their lives. Seemingly they do not think that what they learn is somehow helpful for their lives, for them it is just the certificate. Note: This is a part quotation only. Because of the complexity of Huxley's initial text, it is more economic to quote this way. Any reader may feel free to look up the actual quotation.

[32] The concept of "waste" was seemingly adapted from Henry Ford, who wrote a whole chapter on "Learning from Waste" in his *Today and Tomorrow*. "My theory of waste goes back of the thing itself into the labour of producing it. We want to get full value out of labour so that we may be able to pay it full value" (quoted in Ohno 1978/1988, p. 97).

[33] After WWII, the Japanese economy had only about 10 % of the productivity of the USA. The then president Toyoda Kiichiro wanted to catch up within three years in order to survive. "I still remember my surprise at hearing that it took nine Japanese to do the job of one American. [. . .] But could an American really exert ten times more physical effort? Surely, Japanese people were wasting something. If we could eliminate the waste, productivity should rise by a factor of ten. This idea marked the start of the present Toyota production system" (Ohno 1978/1988, p. 3). The Toyota Production System evolved by repeating *why* five times. "By asking *why* five times and answering it each time, we can get to the real cause of the problem, which is often hidden behind more obvious symptoms" (Ohno 1978/1988, p. 17). The idea is to separate facts from artefacts and to find solutions, which let the problems disappear. In principle, this is relatively close to Mach's idea of enlarging or transforming the view in such a way that the problem disappears.

what is being learnt as well as in the process of learning of the learner (mental orthopaedics). Finally, one should focus on the learning, which has long-term value for life and which remains in the memory of the learner (providing long-term value). The main focus has to be on a sound and consistent foundation of any learning process.[34] Currently instead, quality improvement in education seems mainly (de facto) aimed at enshrining the status quo by formalising it,[35] rather than bringing about such fundamental improvements or even to have such long-term and transformative goals.

Frank Oppenheimer, the brother of Robert Oppenheimer and founder of the Exploratorium – probably the most empirically successful[36] science museum in the world – already in 1981 described the role of the schools in being unintentionally detrimental to learning:

> A large part of the neglect [of learning opportunities such as museums in the popular mind] I think had to do with the extraordinary preoccupation of both school and college teaching faculty with the notion of certification. Educational opportunities, which did not provide any way of certifying the students or of evaluating their performance were relegated to a different domain and were not considered part of the overall process of public education. This preoccupation with certification has been, in fact, a very deadly one. It has produced generations of teachers who teach what they are supposed to teach rather than what they know and want to teach. […] In any event, since museums do not certify and the watching of television shows is not graded or going to libraries cannot be supervised, all of these adjunctive resources for public education have been neglected. [Schools] have taken on, and jealously guarded, the total job of education while having at the same time had to cope with an ever more complicated society and an increasingly mobile population. They have unfortunately failed abysmally. (Oppenheimer 1981, p. 1)

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[34] According to Mach, all initial mistakes or unnecessary metaphysics are repeated and thereby metastasised throughout the whole process. “A problem early in the process always results in a defective product later in the process” (Ohno 1978/1988, p. 4).

[35] As Hattie (2009, p. 109/110) concludes from the meta-analyses in this area, much of teacher education is based on the gut feeling, (quoting Walsh) ““that there is presently very little empirical evidence to support the methods used to prepare the nation’s teachers.” [In my experience] every time the ‘core’ knowledge decided on by a group has been different. […] it seems surprising that the education of new teachers seems so data-free; maybe this is where the future teachers learn how to ignore evidence, emphasize craft, and look for positive evidence that they are making a difference (somewhere, somehow, with someone!). Spending three to four years in training seems to lead to teachers who are reproducers, teachers who teach like the teacher they liked most when they were at school, and teachers who too often see little value in other than practice-based learning on the job”. The challenge is to “unlearn” the perspective of teaching as a student. This requires an *erkenntnis* theoretical reflection of the teacher (who now thinks to know) to imagine the perspective of the learner new to the topic.

[36] I personally know people who have been influenced by the Exploratorium for their lifetime, for instance, becoming rocket scientists, famous writers, etc. Other typical effects and principles of Machian teaching can be found in the observations of K.C. Cole in her biography of Frank Oppenheimer “something incredibly wonderful happens” (Cole 2009). Cole wrote (email 22/08/2012) “many of my other books do [cite Mach], and that thinking came first from Frank [Oppenheimer], but I don’t remember how…”. The observation is typical for the mother’s milk effect described by Einstein regarding Mach. Before intensive research and revisiting old notebooks, also Kurki-Suonio was not aware of where he had his ideas from.

Certification[37] in education has a tendency to promote the production of large groups of below-average performing students. The method by itself does not improve understanding. The low-achieving students are sieved out, while the other part is not taught much new. Certification optimises the maximum passing of a minimum standard. If one sees certification instead as a means of providing a minimum bar *everybody* must cross,[38] finding out who still might require closer attention, at least the method is stripped off its teleology. It would mean that all students must have a minimum understanding of the topic taught. Still such a method is not genetic, though the genetic method is probably the only one providing this effect until now. Nevertheless, standard tests can be used to test genetic teaching versus standard teaching. But such tests will miss out on the most important dimensions of genetic-adaptive learning (the tests are linear, not exponential). They are a poor proxy, though students taught with genetic-adaptive teaching do not tend to have trouble passing, on the contrary.[39] Only if all students pass such tests with the highest possible grade, the tests do not make sense anymore (see Siemsen 1981). The number of students not passing shows the failure of the teacher to teach and not necessarily the failure of the students to learn. The model that the grades in a class must follow a normal distribution is a human convention, not an empirical law. It is not consistent with the teaching goal to teach everybody well.

Mach always saw exams not as a means of testing the knowledge of the student, but to teach the student something general, something the student would be able to use for a lifetime (a method, which in several cases has been described to work by Mach's former students).

For Mach, learning is a continuous activity of all living nature, not restricted to classrooms. Phenomena do not tend to adhere to scientific disciplines, but still require to be observed. In such a view, classroom activity is just a refinement of daily activity into a specific direction. There is no need for artificial borders unnecessarily separating the classroom from learning activities taking place elsewhere. It is the learning, which is the central phenomenon, not the place.

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[37] "One has to go rather slowly on fixing standards, for it is considerably easier to fix a wrong standard than a right one. There is the standardizing which marks inertia and the standardizing which marks progress. Therein lies the danger in loosely talking about standardization. […] no body of men could possibly have the knowledge to set up standards, for that knowledge must come from the inside of each manufacturing unit and not at all from the outside. In the second place, presuming that they did have the knowledge, then these standards, although perhaps effecting a transient economy, would in the end bar progress, because manufacturers would be satisfied to make the standards instead of making to the public, and human ingenuity would be dulled instead of sharpened" (Ford quoted in Ohno 1978/1988, p. 99). Currently, no standardisation system in education is made for improving education by a factor of ten.

[38] The goal of quality management as taught, for instance, by Juran in Japan, which led to the Toyota Production System, is to optimise the process so that it has zero defects. As education is about humans and their lives, the goal of zero dropouts and even zero low achievers should be at least as important in education as in the automotive industry.

[39] In Finland, teachers from Kurki-Suonio's courses already have trouble to measure their performance, because even the phenomenology of the PISA-type tests is insufficient to measure their way of teaching.

The freed time and resources can then instead be spent on helping the students to improve their learning and improving teaching so that more than 5 % remains. In such a way, teaching can be easily improved by several hundred percent with no new resources necessary. The OECD estimates that Finnish students gain ¾ of a year on 4 years of school against German students.

72.4 The Historical-Genetic Background of Mach's Ideas on Science Teaching

What is the central change in Mach's world view in comparison to the previous (antique) world view? The main difference is the transformation in the concept of genesis brought about by many new empirical observations, which Darwin has so consistently put together in his *Origin*.

In the previous 2,500-year-old Aristotelian genetic view (based on Empedocles, see Freemen 1947/1971), animal organs (legs, arms, etc.) were initially "puzzled" together, with more or less fitting results from which only the best (the actual species, some anthropomorphic beings like centaurs and especially humans) were retained. These were the "ideal forms" (species, ideas) subsequently serving as "mould" for further copies (like a signet ring is copied into molten wax). This antique concept of genesis had quite some, but limited applicability. It would fit to some of what we would now call evolutionary phenomena, but not to others. It would explain some prenatal defects, such as Siamese twins, or cloven hands as well as anthropomorphic figures of gods with animal heads, maybe deriving from dreams or observations of masked performances. It would not fit to genetic aspects of evolution, such as fossils or species closer or less related (especially to humans). But in ancient times, such phenomena were not easily observable.

Plato developed a philosophy of knowledge in analogy to this Empedocletian hypothesis. Like the Babylonians saw the stars as the eternally unchanging and ideal gods, the Platonian universe god (in *Timaios*) was ideal and eternal. It was the signet ring, from which the earthly (wax) moulds were formed (with some errors in the process). Similarly, the godly ideas were ideal and eternal. As all souls were born with some divine essence, they could sometimes remember these ideas and thus retain them. Plato wanted to include the idea of *metempsychosis* (reincarnation of eternal souls), already much used by the Eastern religions and philosophies, into his philosophy as well.

For knowledge it meant that in humans potentially ideal (godly) thinking was degraded by earthly experience. Many of the ideas transported in myths thus become archetypes of other ideas (see, for instance, Eliade 1975/1981). Knowledge is seen as fixed forms, which do not change over time. They can only be rejected as false and replaced. Thereby, the differentiation between "true and false" becomes central. The ideas that "errors" are an integral part of knowledge and that knowledge and errors can be "good" or "less good" or "bad" (i.e. completely senseless), like gestalt psychologists suggest (see Koehler 1925/1957 or Lipmann and Bogen 1923), are not part of Plato’s system.[40] As a consequence, the logical components were given priority within the overall world view as logic was seen as god’s ideal way of thinking and detecting erroneous ideas. This view of course tends to be absolutistic rather than democratic, like the society in Plato’s Republic (see also Siemsen 2010c). One tends to claim to know the truth, while other ideas are declared aberrations. Plato’s ideal ideas cannot be developed further. They are the goal (*telos*) for any learning. For teaching, the Platonian goal is in principle already achieved and just needs to be reproduced.

Darwin (1859) in his *Origin of the Species* replaced this antique “organ puzzle” with the idea of an adaptive and transformative non-teleological process over time. Species constantly evolve in an interactive process with the environment. Organs are not puzzled together, but are formed by a long process of small adaptations, which can open new opportunities and thus “transform” into new applications. There is no godly signet ring, but each “mould’ itself creates new “moulds” (though the idea of errors in the reproduction process remains as mutations). No eternal soul needs to be transported from our “inner fish” (see Shubin 2008) to our “human form”.

What does Darwin’s view on species mean for the area of knowledge and ideas? Mach (1883/1888) in his essay *Transformation and Adaptation in Scientific Thought* generalises

> Knowledge is an expression of organic nature. The law of evolution, which is that of transformation and adaptation, applies to thoughts just as well as to individuals or any living organisms. A conflict between our customary train of thought and new events produces what is called the problem. By a subsequent adaptation of our thought to the enlarged field of observation, the problem disappears and through this extension of our sphere of experience, the growth of thought is possible. Thus the happiest ideas do not fall from heaven, they rather spring from notions already existing. (Mach 1883/1888)

As a result, Mach’s method is the genetic method of teaching, i.e. teaching as close as possible to the way how we as humans have biologically and culturally evolved. Biology and culture for Mach are reciprocal processes, which have a *plastic* result.[41]

Plato’s hypothetical analogy of biological genesis and human knowledge thus becomes a singular genetic process through a consistent (and thought economical)

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[40] “The self is no pot into which the blue and the ball just have to drop into so that a judgment [a blue ball] shall result. The self is *more* than a simple unity, and certainly no Herbertian *simplicity*. The same spatial elements, which close to a ball have to be blue and the blue has to be recognized as different from the places, as separable, in order to come to a judgment. [...] If we will see the self not as a monad isolated from the world, but a part of this world and in the midst of its flux, from which it came from and to which it is willing to diffuse again, so we will not anymore be inclined to see the world as something *unknowable*. We are then *close* enough to ourselves and *related* enough to the other parts of the world in order to hope for real *Erkenntnis*” (Mach 1905, p. 462).

[41] He is thus neither a nativist nor a blanc-slate empiricist, but close to modern notions of neuronal plasticity (for instance, by Buonomano and Merzenich 1998).

application of the idea of evolution. There is only biological and cultural evolution as two properties of the same genetic process. In this respect, Plato's conception of ideas is retained.

But then, another aspect of Plato's synthesis must be rejected as inconsistent with the idea of evolution. In the new evolutionary perspective, "forms" are not ideal anymore in an absolute, godly sense, just like species are not ideal, but temporary adaptations. Species as well as ideas are processes and products at the same time. In a Newtonian sense, they "interact over time" with the environment, or they are "reciprocal" as James suggested. Forms are only temporary *gestalts*, resulting from the way humans adapted biologically and culturally (historical genesis). These gestalts become adapted and transformed. They are never final.

From an *erkenntnis* theoretical view, and especially an *erkenntnis* psychological view, this fundamental conceptual change reciprocally requires many other conceptual changes which are based on this question. The empirical meanings of several foundational concepts, such as "knowledge" change, i.e. need to be adapted accordingly. Thus, the *erkenntnis* psychology of education fundamentally changes from the older Platonian/Aristotelian[42] view.

At the time of Mach, the Platonian/Aristotelian view had already been slowly eroded by central facts from various disciplines, which were obviously inconsistent with it. Many scientists (Erasmus Darwin, Spinoza, Herbart, Spencer, etc.) had already tried new syntheses from this, groping for new empirical meanings of concepts and new models regarding humans and nature. Charles Darwin's *Origin* was just a culmination of such efforts. Mach was afterwards the first[43] to develop a fundamentally new world view, including the (partial) synthesis from Charles Darwin and the facts from other sciences (physics, psychology, etc.). But he was unable to finalise (sufficiently stabilise) this view in all aspects during his lifetime.

Although Mach had a strong influence on science education (especially on the development of ideas of eminent scientists), he did not write a complete theory of science education. Thus, his intuition in science education remains more influential than his theory of it. His ideas have nevertheless been very fruitful (see Siemsen 2010a, b, c, d, 2011, 2012a, b). Therefore, an evaluation of the questions leading Mach to his ideas might have a strong effect on the future of science education. In science education, especially regarding the history and philosophy of science teaching, the time might now seem more recipient for his ideas than at Mach's own times.

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[42] Aristotle as a student of Plato shared many of Plato's ideas; though as son of a physician, he was certainly more empirical in the physiological details of the theory.

[43] Mach published the first articles and books in this direction already four years (1863) after the publication of the *Origin*. This was much before Haeckel and Darwin himself wrote on the evolution of humans and human knowledge.

72.5 Mach's Central Ideas: Sensualism, Gestalt and *Erkenntnis* Theory

What are Mach's central ideas for science education? From his synthesis between the Platonian/Aristotelian world view and Darwin's world view, there are in principle three reciprocal areas of application: a consequent basis of all knowledge in its *sensual* origins, the thought-economical reduction of sensual elements to conceptual *gestalts* (*Vorstellungen*) and the *erkenntnis* theory, which provides the overall consistency of concepts as well as a meta- perspective and method for optimising one's own learning.

As Mach takes the psychophysical relations as basis for his world view, the sensual and physical perspectives provide the starting points for exploring this relation and therefore the empirical basis of all knowledge. Thus, in line with David Hume and contrary to the aversion of Plato and Aristotle towards sensuality, Mach postulates that the only possible (and empirical) grounds for concepts are the senses and sensual experiences. Reason and reflection are not something apart from this, some higher faculty of thought, but merely an extension and further development of sensualistic origins.[44]

When Aristotle postulates that "*no bodily activity* has any connexion with the *activity of reason*" (Aristotle 1930, p. 2068) and Plato urges to wait for the "opposing currents" of the senses to abate,[45] for Mach these seemingly "opposing [sensual] currents" (from an adult perspective) are the genetic origins of reason. Instead of Platonic waiting, one can encourage the thought-economical process right from its origins. Just because a suckling cannot speak words (i.e. "call names") does not imply that it cannot think or communicate. On the contrary, the suckling's speaking and reasoning are based on bodily activities. For Mach, there is only the "adaptation

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[44] "Certainly one can judge internally, *without* linguistic expression or *before* it. […] One can easily observe this for clever dogs or children, who cannot yet speak" (Mach 1905, p. 112/113). "The basis of all knowing is therefore the *intuition*, which can be related to something sensually perceived, just vividly imagined or potentially imaginable, conceptualizable. The logical knowledge is just a special case of the formerly described, which is only concerned with the finding of consistency or inconsistency and which cannot be brought about without perception or imagination related to former findings. If we come to this new *finding* by pure physical or psychical chance or by planned extension of the experience by thought experiments […], it is always *this* finding, from which all knowledge [Erkenntnis] grows" (Mach 1905, p. 315).

[45] "… and by reason of all these affections [the "opposing currents" of nutrition and senses], the soul, when encased in a mortal body, now, as in the beginning, is first without intelligence; but when the flood of nutriment abates, and the courses of the soul, calming down, go their own way and become steadier as time goes on, then the several circles return to their natural form [mirroring the ideal thoughts of the Cosmos-god seen in the astronomical observations of circular movement], and their revolutions are corrected, and they call the same and the other by the right names, and make the possessor of them to become a rational being. And if these combine in him with any true nurture [Pythagorean dietary obligations] or education, he attains the fullness and health of the perfect man, and escapes the worst disease of all; but if he neglects education, he walks lame to the end of his life, and returns imperfect and good for nothing to the world below. This however, is a later stage […]" (Plato 1871/1892, Vol. III, p. 463).

of the thoughts to the facts and the thoughts to each other". But the adaptation of the thoughts to the facts must take priority as otherwise the thoughts have no relation to the world and are thus arbitrary. Furthermore, learning – including human learning – has evolved (according to Darwin) over millions of years from the sensual experience and not from some (relatively recent) metaphysical a priori system. Sensualistic learning must therefore be much more effective than rationalistic learning.

For Mach, reasoning is just a (cultural) result of the economy of thought. As one cannot memorise all singular sensual experiences, one needs to economise the thoughts on experience.[46] To describe the result of this process, Mach uses the concept of "gestalt".

72.6 Gestalt Psychology

Mach is known as the intellectual father of the gestalt[47] concept, which first Christian von Ehrenfels (1890) identified as a specific Machian concept. The gestalt psychologists (Wertheimer, Koehler, Koffka, Kaila, Lewin, etc.) developed Mach's gestalt concept into a full psychology (see, for instance, Ash 1995).

In his *Analysis*, Mach (1914, footnote p. 90) describes the origin of his idea of gestalt, which led to his last shift in world view.[48] "Some forty years ago […], in a society of physicists and physiologists, I proposed for discussion the question, why geometrically similar figures were also optically similar. I remember quite well the attitude taken with regard to this question, which was accounted not only superfluous, but even ludicrous. Nevertheless, I am now as strongly convinced as I was then that this question involves the whole problem of visual gestalts. That a problem cannot be solved which is not recognized as such is clear. In this non-recognition, however, is manifested, in my opinion, that one-sided mathematico-physical direction of thought […]".[49]

These ideas of Mach had intuitive influences on physics and mathematics but also on the development of psychology, for instance, on the concept of gestalt and

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[46] Actually, nature economises memory in the sense of Hering (1870/1969). Therefore, gestalts are a plastic psychophysical process between physiological and cultural genesis, not limited to thoughts alone.

[47] The gestalt concept as a holistic concept was already used by Goethe or Herbart, but it did not have the genetic perspective. Only after Darwin, Mach could transform the concept into a "process and product". Therefore, seeing gestalt only as "holism", which one often finds in the literature, is an outdated, pre-Darwinian and in the sense of gestalt psychology inadequate understanding.

[48] There were at least two more shifts in his world view (see Mach 1914, p. 30). Mach had several such gestalt shifts in world view, but this shall not be of concern in this article. One nevertheless needs to be careful when reading Mach, which view he held at the time of writing. Some of the views are not consistent to each other.

[49] This quotation also bears reference to the prior-discussed question of methodological specialisation in science and the (unintended) intuitive training of one's thoughts.

gestalt psychology.[50] The article *On Gestalt Qualities* from 1890 by von Ehrenfels was regarded by Wertheimer and Koehler as the foundational article of gestalt psychology (see Wertheimer 1924, Koehler 1920/1938, and Ash 1995). In the beginning of this article, von Ehrenfels states that his ideas initiated from an intuition he had after reading Mach's *Analysis*:

> My starting point arose from several remarks and hints from E. Mach's "Contributions to the Analysis of Sensations" (Jena 1886) [...]. Mach sets up the, for some people certainly paradoxically sounding, hypothesis that we can immediately "sense" [*empfinden*] spatial patterns [*Gestalten*] and even "sound-patterns" or melodies. And indeed at least the second of these theses not only seemingly, but also from its contents should be undisputedly absurd,[51] if it would not be immediately intelligible, that "sensation" here is used in a different than the usual sense. [...] But if Mach, by using the term "spatial and tonal gestalts", also wanted to stress its simplicity, it becomes clear that he [...] viewed these "gestalts" not as mere combination of elements, but as something new (relative to the elements on which they base) and up to a certain degree independent. [...] I hope to be able to show in the following that Mach [in his reflections] has shown us the way of resolving the problem mentioned. (von Ehrenfels 1890, pp. 249–251)

The problem von Ehrenfels mentions is what William James called *The Knowing of Things Together* (1895).[52] If one takes a "regular" concept of sensation, it is a question of descriptive psychology. For Mach, it becomes a question of genetic psychology. What is "simple" might therefore appear to be simple in its current sensational gestalt but is actually a result of a "complex", i.e. reciprocal genetic process between sensation, physiology, memory and background. Gestalts are not linear (additive); they are adaptive and transformational.[53]

Abstraction therefore is not necessarily a "higher development", but a specialisation of thoughts. This specialisation might be thought economical in some contexts or hindering in others. What is "higher" and "lower" in a cultural sense cannot be judged anthropomorphically from the point of view of a specific culture.[54] Such categories often make no sense in anthropology, as the whole conceptual frames (world views) are different. All concepts might be based on completely

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[50] His other influences, for instance, on the development of genetic psychology (Siemsen 2010b) and Boring (1950), shall not be of concern here.

[51] The German word used here is *widersinnig*, which literally translates as "counter sensual".

[52] Hadamard (1945, p. 65) quotes a description from Rodin: "Till the end of his task, it is necessary for [the sculptor] to maintain energetically, in the full light of his consciousness, his global idea, so as to reconduct unceasingly to it and closely connect with it the smallest details of his work. And this cannot be done without a severe strain of thought". The gestalt (statue) integrates the many details (ideas) into a *global idea*.

[53] Many gestalts are not best recognised in reality, but in caricatures, i.e. when certain properties are overemphasised, while others are neglected. Greek statues in the "classic" times are thus not just idealised bodies. They are idealised beyond the point a body could look like. Egyptian obelisks are not built straight, but slightly curved. Equally, "natural laws" cannot be observed in reality. They approximately describe many facts under idealised circumstances which can never be "achieved" for each single fact.

[54] Similar ideas have been developed by Franz Boas and have been very influential in US anthropological thinking until today (see Stocking 1968). On the closeness of the development of these ideas to Mach and their later influence on the initial ideas of Jerome Bruner, see Siemsen (2010b).

different sets of empirical meanings.[55] Also logic and our current Western concept of number came out of practical requirements and needs. They can thus neither be considered universal nor culturally independent. Because of the dominance of Western culture and the expansion of modern science, they have just been developed by more people over longer time than any other similar conceptual systems from other cultures.

The concept of gestalt also resolves the unproductive questions regarding the initial primacy of "nature or nurture". From a gestalt perspective it makes no sense to try to draw a triangle in one dimension and ask which of its sides has a larger share in its area. If one takes the concept of memory as a general function of evolution (see Hering 1870/1969), the problem disappears as a pseudoquestion.

72.7 Mach's *Erkenntnis* Theory in Science Education

The Machian world view is psychophysical, i.e. its basic "conceptual currency" of comparison (elements) requires switching between a physical and a psychical perspective. From the psychical perspective, the basic elements can be seen as sensual (defined recursively as gestalts). In a historical genesis process, clusters of sensual elements from different domains are synthesised into new gestalts, such as space, time and measurement. The syntheses in turn change the focus of attention to new observations, while neglecting others. Depending on the syntheses made, foundational empirical meanings of pre-scientific concepts are laid, which can help or hinder the acquisition of scientific concepts.

In order to keep all these processes consistent, to integrate them, one needs an *erkenntnis* theory. The *erkenntnis* theory provides the conceptual toolkit, the generality, but even more important the meta-method of consistently combining different methods of learning. It provides the observational meta-perspective on oneself as a learner so that one can optimise one's own learning, detect systematic errors, etc.

For implementing this in science education, Mach suggests, for instance, the use of history as (one) method, "[…] It should be shown in all analogous cases, how the concepts have originated historically, which observations have urged towards them. The most naïve historical exposition is always the best. The discoverer of a truth in natural science and the able student both stand before a new theorem without presuppositions. For both the same way is therefore most natural" (Mach 1876, p. 6). "The teacher using historical material […] will not run into the danger of expecting from the student to understand in one attempt, what could develop in the most

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[55] The difference in observed facts can be so intuitively fundamental that even with long training, one cannot observe them in principle. For instance, Boas observed that he consistently heard phoneme in Inuit language one time as one sound, another time as a different sound. His interpretation was that psychophysically, the factual sound gestalt was in between, but impossible for him to hear in the way the natives would hear it.

important heads but slowly and gradually" (Mach 1876, p. 6/7).[56] "The historical exposition will lead to the comparison of different chapters and thereby separate the fundamental from the accidental and conventional" (Mach 1876, p. 8). "The historical [genetic] exposition will apart from clarity have the advantage that the teaching stops to be dogmatic. Science appears as something evolving, not finished, still to be shapable in the future. Mental educability instead of simple education should be the result of such a teaching" (Mach 1876, p. 9). The use of history for Mach thus mainly serves an *erkenntnis* theoretical function.

Mach elaborates the idea of how to teach in a way to optimise the learning for science education: "[…] The formal education is a seed, which by itself will develop fruitfully. This process is not to be underestimated relative to the positive skills, when the student immediately transfers to the practical life, because then he can easily acquire what is missing by himself. On the other hand, an unnecessarily stuffed head cannot help to lead him in times of need out of the critical situation. Formal education is on the other hand the main goal if the teaching is continued in higher education. Then all elements have to be transformed anyway and have to be taken as material and foundation of the new. It is therefore practical to limit the subject matter as far as possible, but work on it in a *many-sided way*. Only by dealing differently with the same issue, one understands the basis of the method and achieves ability in its usage" (Mach 1876, p. 1/2).

The genetic method is thereby different from the axiomatic method, which starts from basic axioms; it is different from the Socratic method, which starts from (linguistic) definitions (already presupposing a frame or a "background", see Rubin 1921), but as described before, it is also not simply historical, though it makes intensive use of history. "One can certainly provide the student with a broader knowledge by starting from ready-made definitions and concepts, placing ready-made doctrines in front of him and proving them. This method is not even so bad in mathematics, because there the step from the experience [*blosse Anschauung*] to the definition and to the theorem might be very short and can therefore be complemented by each able student. The physical knowledge which is acquired in this way nevertheless always appears as externally imposed. Especially for the student who reflects, sudden gaps of clarity will appear which he will not be able to resolve, if he does not know, how one has arrived at the concepts put at the top" (Mach 1876, p. 2/3).

One way of implementing this is by letting the students guess the "success" of an experiment before it is conducted. "Not only thereby the attention is increased, but youths will from the errors which occur in this also draw the lesson that natural laws cannot be philosophized-forth [*lassen sich nicht herausphilosophieren*]. A body does not, as most will guess, in double the time also fall double the way. The pendulum of fourfold length does not also show the fourfold duration of oscillation. One here does not have to construct *a priory*, but to observe" (Mach 1876, p. 20/21).

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[56] Quoted with permission of the Philosophical Archive of the University of Konstanz. All rights reserved.

72.8 Mach's Successors

The successors of Mach, who had Machian effects in their teaching, are William James, Alfred Binet, Eino Kaila, Kaarle Kurki-Suonio, Karl Hayo Siemsen, Martin ernohorský, Rudolf Laemmel, Eugenie Schwarzwald, Frank Oppenheimer, Alexander Israel Wittenberg, Max Wertheimer, Abraham S. Luchins, Adolf Hohenester and John Bradley.

There are several people who used at least part of Mach's teaching ideas in their teaching philosophy, but probably not enough to produce the exponential effects (though this has not been studied in all detail in every case): John Dewey, Otto Blueh, Jerome Bruner, Benchara Branford, Catharina Stern, Eric M. Rogers, Peter Drucker, Paul A. Samuelson, Wilhelm Ostwald, Henry Edward Armstrong, Edgar W. Jenkins, Martin Wagenschein, Georg Kerschensteiner, Spiru Haret, Efraim Fischbein, Solomon Marcus, Joachim Thiele, Robert Wichard Pohl, Walter Jung, Fritz Siemsen, Hugo Kükelhaus, Hans Freudenthal, George Sarton, Alfred N. Whitehead, James Conant, Gerald Holton, Frank Wilczek, K. V. Laurikainen, Edouard Claparède, Théodore Flournoy and Jean Piaget. Many more educators have been inspired by Machian ideas; though after several generations, these "mother's milk" effects become increasingly difficult to trace and to make explicit.

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Kaarle Kurki-Suonio wrote a series of schoolbooks titled *Galileo* and a book on his method, which are currently available only in Finnish.

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[57] The other PISA studies are equally interesting, but will not be cited, as the general issues discussed here can be taken from any single one of them

Hayo Siemsen is working on his habilitation on Mach's influences and his ideas on the philosophy of education and the psychology of research. He is also member of the Ernst Mach Institute for Philosophy of Science and member of the newly founded international Institute for Processes of Learning. His Ph.D. theses were focused on innovation systems, especially on the question if one can learn to be innovative. In various publications he covered a wide range of areas, including education, psychology, economics, management, history, methodology and philosophy/*erkenntnis* psychology of mathematics. The publications are following Mach's general ideas and broad influences rather than scientific categorisations. Recently he published a series of articles in *Science & Education* on Machian education, especially in Finland in comparison with other, similar science education.

Chapter 73
Frederick W. Westaway and Science Education: An Endless Quest

William H. Brock and Edgar W. Jenkins

73.1 Introduction

> I fear that during my professional career, I advocated the claims of science teaching much too strongly, and I am now quite sure that the time often devoted … to laboratory practice, and to the purely mathematical side of science, more especially chemistry and physics, was far too great. (Westaway 1942a, p.v)[1]

So wrote F. W. Westaway, teacher, headmaster, His Majesty's Inspector (HMI) and eloquent advocate of science education, in the preface of his last book, published in 1942, with the intriguing title *Science in the Dock: Guilty or Not Guilty?* Who was Westaway, what influence did he have upon school science teaching and what had prompted him to raise and address this question?

Frederick William Westaway was born on 29 July 1864 at Cheltenham, Gloucestershire, the first of seven children of William and Caroline Westaway, three of whom died in infancy. It seems clear that the family circumstances were extremely modest. His father was a travelling blacksmith, and his mother (to judge from the mark she made on Frederick's birth certificate) was unable to write. Westaway later recalled receiving his first chemistry lesson at the age of 10 in 1874. It was given by the Gloucester Public Analyst[2]:

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[1] The preface was dated September 1941. He had expressed similar doubts following WW1 in a new preface to the 2nd ed. of Westaway (1919, p. xii).

[2] Probably John Horsley, a founder member of the Society of Public Analysts in July 1874. He specialised in the analysis of milk and dairy products. Westaway joined the Chemical Society in June 1892.

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> There was no laboratory available, but there was a well-fitted lecture room, and in later lessons a few gases were prepared. But the first lesson, which extended over an hour, was frankly a lecture on the atomic theory. No experiments whatever were performed, but the formulae and equations which covered the blackboard impressed at least one small boy. (Westaway 1937a, p. 490; Westaway 1929, p. 18)

By 1881 the family had moved to Ruardean in Gloucestershire's Forest of Dean, where Frederick's father was landlord of a public house.[3] By then Frederick was a pupil teacher at the village school from where he enrolled at St John's Training College in Battersea and began his formal teaching career in London in 1886 (Westaway 1929, p. 19). Concerning this experience, he provides a personal anecdote of some historical interest. He was allocated two hours for chemistry and two hours for mechanics.[4] He had no laboratory or demonstration bench and only a balance that he had made himself. The Bunsen burner had to be fed from the gas pendant above the pupils' heads. Using Ira Remsen's revolutionary American textbook, he proceeded to teach (Remsen 1886):

> In the middle of a lesson on equivalents, two visitors whose names I did not catch were shown in, and they sat down and listened. When I had finished they came up and showed what I thought to be a surprising appreciation of what I had been doing, and eventually one of them said: "Do you happen to know Roscoe's book on chemistry?" "Yes," I replied, "and a thoroughly unsatisfactory book it is. The writer makes unjustifiable assumptions about chemical theory before he had established necessary facts. It is the kind of thing that no teacher ought to do." At this stage the second visitor interposed and said, "I think, perhaps, you are asking for trouble. Let me introduce you to Professor [afterwards Sir Henry] Roscoe." However, in spite of the criticized book, I learnt more about the teaching of chemistry in the next quarter of an hour than I might have learnt in the next ten years. In particular, I learnt a much needed lesson – that there is more than one avenue of approach to the teaching of science, and that it is sheer folly to assume that science must be taught according to one pedagogue's prescription. (Westaway 1929, pp. 19–20)[5]

He lodged in Lambeth, joined the rifle volunteer movement, passed his London Matriculation examination in 1887 and graduated BA from the University of London in 1890. It was a career path followed by a significant number of the more able pupil teachers in the last two decades of the nineteenth century, and many of them found employment in the growing number of post-elementary schools, known as Higher Grade Schools, established by the School Boards in larger towns and cities (Vlaeminke 2000). From hints in his later books, it appears that Westaway continued his self-improvement by attending evening classes and the summer schools for science teachers that were run by Frankland (chemistry), Guthrie (physics) and Huxley (biology) at South Kensington under the auspices of the Department of Science and Art (DSA).

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[3] Later, between 1897 and 1901, William Westaway was landlord of the George Inn, Market Street, Gloucester.

[4] This may imply that the bulk of his timetable was spent in teaching more general subjects such as English and Latin.

[5] For Roscoe's textbook, ironically published in the same Macmillan's Primer Series as Remsen's book, see Roscoe (1866; new ed. 1886). The other visitor was the chemist and educationist John Hall Gladstone, as revealed in Westaway (1936, p. 313).

In May 1892, when teaching at a school at Stockwell in south-west London, Westaway married Mary Jane Collar, the daughter of a pianoforte maker and herself a teacher.[6] Her two brothers, George and Henry, were also teachers, and both eventually became headmasters of London schools. The newly married couple immediately moved to Dalton in Furness[7] where he had been appointed headmaster of the Higher Grade School, the local Board School having been established in 1878. Westaway thereby began his formal connection with South Kensington since the school would have been recognised as an organised science school for the purposes of DSA grants. The chief local industries were iron ore mining and quarrying, and the School Board, like that in other northern towns in England, recognised the need for a better-informed and technically competent workforce. It is alleged that Westaway grew a beard to hide his relative youth. Their only child, Katherine Mary, was born in the School House in 1893, and her father was to exert an important influence upon her upbringing and career. She eventually became a distinguished classical scholar and an outstanding headmistress of Bedford High School from 1924 until her retirement in 1949.

Clearly ambitious, Westaway moved from Dalton in Furness to Bristol in 1894 to become headmaster of the newly built St George's Secondary and Technical School which contained "a thoroughly well-appointed Chemistry Laboratory, a large Science Lecture Room, a Workshop, a Dining Room and accommodation of every kind conducive to the well-being of the scholars".[8] Its finances were entirely contingent upon the school's ability to earn grants by Westaway's pupils gaining high passes in the examinations run by the DSA. A local newspaper reported:

> The [School] Board considered a number of applications for the appointment of the St George Higher Grade School. Mr *F. W. Westaway*, at present holding an appointment at the higher grade schools, Dalton-in-Furness, was appointed unanimously. In his application his University distinction was stated to be (a) B.A. London; Inter B.Sc., final examination, deferred until 1895; (c) Member of Convocation of the University of London. The list of qualifications, particulars of past experience, copies of testimonials, and prospectus of present school were considered by the Board highly satisfactory. (Anon 11 October 1894)[9]

Vlaeminke's study of the school's logbooks reveals that Westaway taught all the science and mathematics himself and triumphantly gained passes for his pupils in the DSA examinations that were the best in the Bristol area. No doubt this was

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[6] The ceremony was conducted at St Matthew's Church, West Kensington (Mary Collar's parish), by Edwin Hobson, the principal and chaplain of St Katherine's College, Tottenham, where Mary had trained to be a teacher. The college, which had been set up originally by the Society for the Promotion of Christian Knowledge in 1878, is now part of Middlesex University. Hobson had been vice-principal of St John's College, Battersea, from 1874 to 1877 before Westaway was a student there.

[7] Dalton in Furness lies on the southern edge of the Lake District in Cumbria (until 1974 in Lancashire). It is famed for its castle and for Furness Abbey. The school, which opened in 1877, survives as an infant school.

[8] This was Bristol's first state secondary school created by local entrepreneurs in 1894. Its premises, which are currently used as a Sikh temple, were opened in 1894. Following various changes of name, it moved to new premises in 2005 as St George City Academy.

[9] The school's development is analysed in Vlaeminke (2000).

noticed by the Department of Science and Art for, within a year, Westaway was offered a subinspectorship in the department. On the face of it, accepting this offer was an odd decision, for although the character of the DSA was changing during the 1890s, the task of its inspectors largely remained one of ensuring that its militaristic rules and regulations for the conduct of examinations and payment by results were strictly adhered to (Butterworth 1982, pp. 27–44). The appointment to the inspectorate probably involved a drop in salary, though this would have been compensated by the prospect of a very good pension.[10]

Westaway's movements between 1895 and the passing of the (Secondary) Education Act of 1902 are unclear. He was undoubtedly not content to sit on his laurels but continued his studies at the Royal College of Science at South Kensington in London where he was a prizeman in mathematics and physics. By 1901, however, his post in the civil service had become that of one of Her Majesty's Inspectors of Education with responsibilities for secondary education in the area of Essex.[11] It was here that their daughter Katherine, together with two friends, began her first lessons with a governess (Kitchener 1981; Hunt 2004), and Westaway cultivated a friendship with R. J. Strutt, 3rd Baron Rayleigh, who kept a private laboratory at his home at Terling Place, near Chelmsford. Within a year, however, Westaway took over responsibilities for inspection in the Bedfordshire area. The family moved to Pemberley Crescent in Bedford, close to Bedford School.[12] He remained an HMI until his retirement in 1929, when he moved to the village of Aspley Heath, adjacent to Woburn Sands in Bedfordshire. He was intensely proud of his profession and of the intellectual attainments of the colleagues with whom he mixed. He sometimes indulges in name-dropping: for example, when mentioning the Irish physicist Thomas Preston (1860–1900), he refers to him as "for some time an esteemed colleague of the present writer's" (Westaway 1937a, p. 364).[13] Preston did, indeed, combine his chair of natural philosophy at Trinity College Dublin with a government post as an inspector of science and art for Irish schools, but it seems unlikely that Preston ever came into direct contact with Westaway.

73.2 The Philosophy of Science

During his long life, Westaway authored some sixteen books, many of which ran into several editions, although not all were concerned with science education. His first book, *Scientific Method: Its Philosophy and Practice*, was published in 1912.

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[10] On the recruitment of inspectors, see Gosden (1966, p. 25).

[11] The 1870 Education Act abolished the denominational character of the inspectorate and reorganised HMIs territorially to reduce their travel. This system continued after the reorganisation of secondary education following the Education Act of 1902. See Gosden (1966, pp. 27 and 111). The Westaway family moved from Bristol to 87 Camden Villa, Fuller's Road, Woodford, Essex.

[12] According to 1901 and 1911 Census data, the Westaways employed one servant girl.

[13] For Preston, see Weaire and O'Connor (1987).

The date is significant since it coincides with the growing scholarly interest in the history and philosophy of science, evident, for example, in the first publication of the journal *ISIS* by George Sarton in Belgium in 1913. Westaway dedicated his book to the physicist Lord Rayleigh (1842–1919) "to whose work and whose teaching the author is deeply indebted" (Westaway 1912, p. 439).[14] The first edition of *Scientific Method* was in four parts. The first examined philosophical issues and offered a commentary upon the ideas of a range of philosophers including Plato, Aristotle, Francis Bacon, Descartes, Locke and Hume. This was followed by attention to Victorian "methodologists" such as Whewell, Mill and Herschel and a discussion of what might be meant by such terms as induction, deduction, scientific law and hypothesis. The third part of the book turned to the history of science and was devoted to "Famous men of science and their methods". In this section, scientists such as Harvey, Newton, Black, Priestley, Faraday, Wallace, Darwin, Clerk Maxwell, Ostwald and J. J. Thomson were largely allowed to speak for themselves through the form of generous quotations. The book ended with a practical section for science teachers entitled "Scientific method in the classroom" in which Westaway offered examples, drawn from botany, chemistry and physics, of what today would be called teaching by investigation.

Nature thought the book is "a model of clearness" and ideal for both science teachers and the general reader. Its sole fault, if any, was the use of excessive quotations, though the reviewer put this down to the fact that Westaway was exceptionally well read (JAH 1912).[15] The reviewer missed the fact that Westaway was concerned with more than promoting a greater understanding of the history and philosophy of science. As he made clear in his preface, he was anxious to bring humanists and realists (i.e. scientists) closer together and to reconcile the ideals which they represented. The need for such reconciliation was to become particularly urgent during the First World War when something of a battle of the books broke out between the scientific community and those representing the humanities, over the contribution that science could make to liberal education.[16] One outcome was the claim, already promoted in Westaway's book, that the history and philosophy of science offered a means of humanising a narrow, specialised and otherwise dehumanising scientific education.

The second edition was published immediately after the war had concluded in 1919. A new preface blamed Britain's industrial problems on its "continued use of haphazard methods". It would be the undoing of the nation if this were continued:

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[14] Also Westaway (1919, 2nd ed., p. 426), Westaway (1924, 3rd ed.), Westaway (1931b, 4th ed. "revised and enlarged, present-day methods critically considered") and Westaway (1937a, 5th ed.). Most of these editions are available online. According to the *World Catalogue,* Chinese translations were made in 1935 and 1969.

[15] The reviewer was probably the chemical physicist John Alexander Harker.

[16] There is a large literature on the theme of humanising the science curriculum. See Jenkins (1979, pp. 54–55), Brock (1996, Chap. 19), Mayer (1997), Donnelly (2002, 2004) and Donnelly and Ryder (2011).

> On the one side we have Germany, clear-headed and thorough; America, original and enterprising; Japan, self-denying and observant; France, pain-staking and clever: all four nations believers in *work*. On the other side we have Britain, insular and unsystematic, looking upon work as a nuisance because interfering with pleasures. (Westaway 1919, p. xii)

An appendix, "Retrospect and Reflections 1912–1918", continued this theme, going so far as to assert that Britain had not won the war because of science or education but because of the reawakening of the nation's dormant national qualities. For their part, the Germans had lost because of their servility to authority and inability to think for themselves. Westaway's solution, overtly political, involved the redistribution of wealth and the wholesale application of scientific method. The "Retrospect" surveyed the functions and influence of science and scientific method on national life. This time the *Nature* reviewer, noting how the Thomson Report on Natural Science Teaching had urged science teachers to become acquainted with the history and philosophy of science, recommended the volume enthusiastically as enlightening and helpful. "Clearly presented" with "apt and instructive" examples, "any science teacher, whether at university of school, who reads the book, cannot fail to derive profit and interest from it" (Anon 1920a).[17]

By the time the 4th "revised and enlarged" edition had appeared in 1931 (a third edition in 1924 merely expanded the chapter on the theory of relativity), Westaway was a lot more sanguine about Britain's future. Post-war society, he suggested, had become less rule of thumb, more rational and systematic. He expressed delight in the progress of mass production with its implicit inclusion of specialisation, expertise and machinery in the operations of industry. Even so, there was still need for "the development of the scientific study and impartial examination of all the complex factors, economic, social, political, and racial, involved in controversial problems which are the sources of international friction" (Westaway 1931b, p. xii). Westaway clearly believed that the revised version of his book would help teachers produce a workforce geared to a mass-production society. To that end, he added a fourth section on present-day methods in contemporary science – including nuclear physics and quantum mechanics – and a fifth section on how scientific method could be inculcated in the classroom and lecture theatre.

In the final edition, published well into his retirement in 1937 and which received a Chinese translation, two further sections were added: one giving excerpts from the writings of "distinguished workers of the day" whom he obviously admired[18] the other offering further examples of the application of scientific methods for advanced students (Westaway 1937a). This extraordinary section included the analysis of historical facts using the example of the causes of the decline and fall of the Roman Empire, as well as an open-ended discussion of whether there was a criterion of excellence in aesthetics – a subject that he was to expand in another book.

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[17] The unsigned review was probably by the editor, Richard Gregory, whose much reprinted book *Discovery* (Gregory 1916) was admired by Westaway.

[18] These included Max Born, Herbert Dingle, Julian Huxley, James Jeans, Hyman Levy, Max Planck and Walther de Sitter.

73.3 Science Teaching

Westaway had included a short section on scientific method applied in the classroom in *Scientific Method* in 1912 and the subsequent editions, but it was not until his retirement that he expanded it as a separate book in 1929. Dedicated to his friend and superior in the inspectorate, Francis B Stead, *Science Teaching: What It Was, What It Is, What It Might Be* was a volume that sought to assert the liberal values of a scientific education, providing always that science was well taught. From this perspective, *Science Teaching* follows the tradition of earlier works by Mach (1893) and Dewey (1900, 1902, 1916),[19] a tradition that was to be sustained in subsequent years by the writings of Schwab (1982), Conant (1947, 1957), Holton (1952) and many others. It also owes something, and not simply as far as its title is concerned, to Edmond Holmes' seminal volume, published in 1911, *What Is and What Might Be* (Holmes 1911),[20] and to Stead's work as secretary (and compiler) of J. J. Thomson's influential wartime report on *Natural Science in Education* (Stead 1918).[21] Drawing upon his experience as an HMI – he speaks of witnessing "1000 lessons a year for over 30 years" (Westaway 1929, p. xii) – Westaway argues in *Science Teaching* for a broadening of school science education to include some biology, astronomy and palaeontology and sets out the case for making science a compulsory part of the school curriculum. But the book is more than this. It is also a primer of practice and a challenge to those whose educational "claims on behalf of science … are sometimes tinged with a good deal of arrogance and intolerance, and whose advocacy is thus better calculated to make enemies than enlist friends" (Westaway 1942b, back cover).[22] Once again, Westaway is seeking to promote a middle way in education, one in which there is "no natural antagonism between science on the one hand and humanism on the other" and one in which the history and philosophy of science play a key part. Such an ethos was shared with another significant HMI, the historian and positivist, Francis Sydney Marvin (1863–1943).[23]

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[19] Mach (1893) first appeared in German in 1883. It remained in print throughout Westaway's career. Westaway frequently cited and recommended Mach in his writings, but not Dewey.

[20] Holmes (1850–1936), who became chief inspector of elementary schools in 1905, resigned in 1911 over criticisms of HMIs who had formerly been elementary schoolteachers. See Gordon (1978) and Shute (1998).

[21] Chaired by the physicist J. J. Thomson, the report was actually compiled by the committee's secretary, Francis Bernard Stead (1873–1955), H. M. chief inspector of secondary schools and a close friend of the Westaways. Stead, a Cambridge NST graduate, had worked at Plymouth's Marine Biology Association and Clifton College before joining the inspectorate in 1908. The science report was one of four (science, classics, English, modern languages) eventually prepared by the Board of Education. See *Nature* 175 (1955), pp. 148, 175) and Jenkins (1973, pp. 76–87).

[22] A 4-page publisher's pamphlet of "press appreciations" (c. 1930) in the possession of WHB carries the quotation from *Journal of Education*: "Get the book and read it; it is the best thing yet".

[23] Marvin, August Comte's principal spokesman for positivism in Britain, was an HMI from 1890 to 1924. He played a major role in improving the teaching of history in schools. See Mayer (2004). Curiously, despite his influence on the teaching of history, Marvin has not been included in the *Oxford DNB,* whereas his wife, Edith Mary Marvin (née Deverell) (1872–1958), a fellow HMI,

Westaway's definition of a successful science teacher (ignoring his gender bias) may be demanding and an ideal, but it still suggests what is required in the profession:

> He knows his own special subject through and through, he is widely read in other branches of science, he knows how to teach, he knows how to teach science, he is able to express himself lucidly, he is skilful in manipulation, he is resourceful both at the demonstration table and in the laboratory, he is a logician to his finger-tips, he is something of a philosopher, and he is so far an historian that he can sit down with a crowd of boys and talk to them about personal equations, the lives, and the work of such geniuses as Galileo, Newton, Faraday, and Darwin. More than all of this, he is an enthusiast, full of faith in his own particular work. (Westaway 1929, p. 3)

Little wonder that he admitted that he thought a teacher was not really fully equipped to teach effectively until he was in his thirties.

Science Teaching, with its extensive syllabus suggestions and advice on laboratory accommodation and equipment, as well as its helpful discussion of classroom practice, was well received by the reviewers ("a book of outstanding usefulness", "remarkable, critical and stimulating"), and it became a staple of initial training courses for graduate science teachers.[24] His suggestions that the periodic law and wave motion (not energy) should be the pole stars of the school chemistry and physics syllabuses were undoubtedly influential, as was his emphatic insistence on the introduction of biology into the secondary curriculum. Like the rest of Westaway's books, it is characterised by a directness and lucidity of style and by the author's capacity to engage with a wide range of disciplines and to draw his arguments and examples accordingly. The book was reprinted in its year of publication and again in 1934, 1942 and posthumously in 1947. Even today, much of Westaway's advice to those learning to teach science has the ring of experience. Some of his questions for young science teachers or pupils leaving school remain both challenging and of interest. For example,

> Do you consider that the estimates of stellar distances and electronic magnitudes correspond approximately with actual fact? What part of the available evidence is experimental and what part is inferential? Is the latter evidence convincing?
>
> How would you estimate the number of flaps made in a second by the wings of a flying bluebottle?
>
> Some years ago a science teacher, working single handed, was trying to extinguish the burning woodwork (pitch-pine) of a fume cupboard … when he was called to a boy who had become unconscious through the inhalation of chlorine. How would you have coped with the double emergency?

Further insights into Westaway's views on science teaching are revealed by an appreciation he wrote for *The School Science Review* of Henry Edward Armstrong, following the death of the latter in July 1937. Westaway had come into contact with both Armstrong and Thomas Henry Huxley as early as the 1880s while studying at

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has. The same has happened with Westaway and his daughter, Katherine. Both Marvin and Westaway are to be included in a forthcoming update of *ODNB*.

[24] For an appreciative review by the science teacher and historian of science, Eric Holmyard, see Holmyard (1929). Note also the appreciation of the Latymer School science teacher George Fowles (1937, pp. 13, 501, 513, 527).

the Royal College of Science, and he thus constitutes a direct link with some of the leading figures in the late nineteenth-century education.[25] It is clear from Westaway's *Science Teaching* that it was Huxley who exercised the greatest influence upon his ideas, and he was intensely proud to have been personally examined by Huxley in biology. For Westaway, the purpose of a scientific education was the making of Huxley's "cold logic engine", in which "the desire for discriminating evidence" would become a "predominating factor" in thinking.[26] Nonetheless, he found Armstrong's heurism, with its commitment to teaching "scientific method", an approach to science teaching in which "practice simply would not yield to precept" (Westaway 1929, pp. 20–27).[27] The imparting of information was a vital function of teaching, and this was the cardinal fault of heurism in its pure form. Moreover, heurism was "not new" but, in essence, a strategy "used by intelligent teachers all down the ages". For Westaway, therefore, Armstrong's great contribution to science education was not heurism itself but the fact that he compelled others to keep their "defensive weapons keen and bright" and be "ever ready to defend alternative methods". Armstrong, he thought, had given hostage to fortune by calling his system the heuristic method instead of, say, "the search" or "discovery method" (Westaway 1929, p. 20). However, he admired Armstrong as a teacher and had high praise for his account of chemistry in the 13th edition of *Encyclopaedia Britannica* (1926) for the way it cast light on the inner nature of chemistry.

73.4 Mathematics Teaching

It would seem that Westaway's first love as a practising teacher was mathematics. In several places, he lamented the loss of Euclid due to the efforts of the former Association for the Improvement of Geometrical Teaching. Nevertheless, he became a keen member of its successor, the Mathematical Association, and a regular reader of its *Mathematical Gazette* (Price 1994). He published two geometry textbooks for private and state secondary schools and technical colleges which differed only in that the latter contained additional material for middle-form boys up to the age of 14 (Westaway 1928a, b).[28] The texts were addressed directly to both teachers and

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[25] "Faith in my own old teachers –Thomas Henry Huxley, John Tyndall, John Hall Gladstone, and (the 3rd) Lord Rayleigh – is as strong as ever, all of whom, in season and out of season, insisted on laboratory and field work first and always, on *facts* and ever more facts" (Westaway 1936, pp. ix, 359, and 745). He also recalled the wonderful lecture demonstrations of Charles Vernon Boys in Westaway (1936, pp. 692).

[26] Westaway was quoting from Huxley (1905, pp. 76–110).

[27] See Brock (1973; reprint 2012).

[28] Westaway (1928a) covered the geometry syllabus from age 8 to 13 when the common entrance examination for admission to a public school was taken. Westaway (1928b) must have been published a few months after the other geometry textbook. Both texts mentioned Westaway's admiration for the geometry lessons of his "friends" Frederick William Sanderson (1857–1922), headmaster of Oundle School, and Edward Mann Langley (1851–1933), a teacher at Bedford Modern School and founder-editor of *The Mathematical Gazette.*

pupils, the latter being expected to read a chapter before it was discussed with them. In line with contemporary feelings about geometry teaching, Westaway avoided deductive proofs from first principles. Long chains of reasoning were also avoided, and intuitive reasoning was frequently used, while practical examples from surveying and carpentry demonstrated the practical significance of geometrical reasoning.[29] Typically, Westaway supplied a list of Latin words and the mathematical expressions derived from them in the expectation that teachers and pupils would correlate their mathematical and classical learning.

In 1931, following the tremendous success of his book on *Science Teaching*, Westaway's publishers suggested that a similar book addressed to mathematics teachers was a desideratum. The result was another remarkable handbook offering young inexperienced teachers advice and useful hints on putting mathematics across in the classroom (Westaway 1931a). Although entitled *elementary* mathematics education, the 28 chapters in fact ranged from simple addition and subtraction to teaching the calculus and thus covered the whole of school mathematics from the level of infants to university entrants. As one reviewer remarked (Anon 1931), Westaway's standard for what a pupil should know was very high, citing as evidence the casual remark that a 4th-form boy was apt to forget the factors of $a^4 + 2a^2b^2 + b^4$ [i.e. $(a^2 + b^2)^2$]. (Was this a reflection of a decline in expectations or merely due to the fact that Westaway's treatment smacked of the nineteenth, rather than, the twentieth century, as the same reviewer suspected?) There were also sections on mathematics in astronomy and biology (a field Westaway foresaw as developing in significance), time and the calendar (which he thought was the job of mathematics staff to teach), as well as on non-Euclidean geometry and the history and philosophy of mathematics. Westaway specifically addressed *new* teachers rather than experienced accomplished instructors, thus ensuring, like his treatise on science teaching, the book's heavy use in British teacher training colleges and ready sale among tyros. Its valuable suggestions for organising the math curriculum throughout a school must also have recommended it to senior staff as well. Curiously, and surprisingly, the Mathematical Association ignored the book, though it was reviewed favourably and at length by the Harvard geometer Ralph Beatley who recognised that many of the problems delineated by Westaway were common in America as well (Beatley 1933).

73.5 Language Teaching

Westaway had clearly taught Latin at an early stage of his career and had a deep respect for classical education.[30] Although we think of him primarily as a science educator, he also made an informative contribution to classical teaching in the form of his second book *Quantity and Accent in the Pronunciation of Latin*, which he

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[29] This practical aspect was praised by Dobbs (1929).

[30] His love of the classics was inherited by his daughter Kathleen who lectured in classics at Royal Holloway College (1920–1924) before becoming headmistress of her old school. See Westaway K. W. (1917, 1922, 1924).

published in 1914 (Westaway 1914).[31] Westaway was adamant that it was not a textbook and that it was not aimed at schoolteachers. His targets were private students of Latin and those whose knowledge of the rules of pronunciation was rusty. The context was a contemporary debate between an older generation of classicists who wanted to continue using an Anglicised "easy-going" form of pronunciation and the younger generation of classicists whose knowledge was informed by research in philology and phonetics. "Mr Westaway's heart is in the right place", that of a reformer, concluded Edward Adolf Sonnenschein, the professor of Greek and Latin at the University of Birmingham, and "he writes with conviction" (Sonnenschein 1914, pp. 213–214). That the text did well in modernising the teaching of Latin is suggested by the fact that it remained in print in the 1920s and that an enlarged edition appeared in 1930. The text had been read with approval by both John Percival Postgate (1853–1926), professor of Latin at the University of Liverpool and the founder (with Sonnenschein) of the Classical Association in 1903, and Westaway's superior in the Education Department John William Mackail (1859–1945), an eminent Virgil scholar. Westaway became a life member of both the Classical Association and the Modern Languages Association in 1903. Like the British Association for the Advancement of Science, which he also joined in 1903, Westaway must have seen these organisations as a valuable way for an HMI to keep up to date.

In *Scientific Method*, Westaway's concern for logical thinking took him into one of his many other interests, language and clarity of thought and expression, and hence into the use of words to express causality. It seems he regarded English grammar as offering important philosophical insights for the science teacher. In his inspections of schools and technical colleges, not unexpectedly, Westaway came across poorly expressed written reports of experiments. More surprisingly, he came across ungrammatical and illogical prose in reports by scientists in periodicals such as *Nature*, which he evidently read each week. Another periodical he read regularly, but never contributed to, was the *Mathematical Gazette* which had been founded by the Mathematical Association in 1894. Westaway joined the association in 1914. He was impressed and inspired by his chief in the inspectorate, W. C. Fletcher, who published an article in the *Gazette* in March 1924 stressing that mathematicians should write good prose between their symbols (Fletcher 1924).[32] Fletcher's essay, together with the earlier appearance of George Sampson's influential report on the teaching of English in 1921 (Sampson 1921),[33] probably inspired Westaway to publish *The Writing of Clear English* in 1926. While significantly subtitled *A Book*

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[31] This was the only one of his books not published by Blackie. Note also Westaway (1933a).

[32] Fletcher (1865–1959) is best known for "Fletcher's trolley", an improvement on Atwood's machine for teaching mechanics. After graduating from Cambridge as 2nd wrangler in 1887, Fletcher taught at Bedford School (1887–1896) before becoming headmaster of the Liverpool Institute (1896–1904). He was appointed Chief Inspector of Secondary Schools in 1904. He retired in 1926 only to teach at the girls' school where his daughter was headmistress. See obituary (Anon 1959).

[33] Sampson (1873–1950) followed a similar path to Westaway – pupil teacher, London Matric, teacher, headmaster, district inspector for London County Council.

for Students of Science and Technology, its clear exposition of the principles of English grammar and advice on sentence and paragraph construction and logical writing style would have made it useful to a generally educated readership that found itself in need of English improvement (Westaway 1926).[34] In retirement, Westaway revised and enlarged the book as *The Teaching of English Grammar Function versus Form* (Westaway 1933b).[35]

In 1932 Westaway persuaded his publishers to launch a series of books offering instruction and advice to teachers under the umbrella title of The Teachers' Library. Although Westaway did not write a book specifically for the series, he recruited the help of other HMIs and acted as the advisory editor for the series. The library was planned "for the guidance of teachers whose daily work is concerned with children of eight and upwards" (Finch & Kimmins 1932, Preface).[36]

73.6 History of Science

As we have seen from both his *Scientific Method* and *Science Teaching*, Westaway believed that teachers should tell stories about great mathematicians and scientists. He also thought sixth-form students should be encouraged and challenged to read, among other original works, Newton's *Opticks*, Faraday's *Researches on Electricity* and Darwin's *Earthworms* (Westaway 1929, p. 383). The interwar years were a particularly productive time for Westaway. In addition to books on the teaching of mathematics, geometry and English (for science specialists), he wrote a large volume of over 1,000 pages entitled *The Endless Quest: Three Thousand Years of Science* (Westaway 1934).[37] This huge, richly illustrated volume is something of a tour de force, and, even today, when specialised degree courses are available in history of science, as a history of science published in 1934, it makes appealing and, in places, challenging reading. Westaway's originality is shown in his deliberate attempt to write a critical appraisal of scientific development and to show its weaknesses as well as its strengths. He acknowledged the influence of his departmental colleague, the positivist historian Sydney Marvin, who was a friend of George Sarton and who was keen to see history of science taught by history teachers. An anonymous reviewer in *The School Science Review* described the book as "a veritable encyclopaedia of science", adding that only "a writer of extreme scientific versatility" could attempt to write it (Anon 1935; Dingle 1935).

Internal inspection shows that Westaway's sources included the British Library and books borrowed from H. K. Lewis, the scientific and medical library

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[34] One teacher thought he had "done his work well". See Anon (1927).

[35] For context, see Hudson and Walmsley (2005).

[36] Unfortunately, because in most scholarly libraries books are catalogued by authorship, it is not possible to identify all the books in the series except serendipitously.

[37] 2nd ed. 1935 with minor corrections only; reprint 1936. Chinese translations 1937 and 1966, Czech in 1937. The book of 1,080 pp was dedicated to his daughter.

in Gower Street, the *Encyclopaedia Britannica* and *Nature* as well as his own well-stocked library. The ready availability of Boyle's *Sceptical Chymist* and Harvey's *On the Motion of the Heart* in the Everyman Library enabled him to give detailed accounts of their experiments and reasoning. Westaway's historiography was surprisingly sophisticated for a period when accounts of science were usually triumphalist and Whiggish. When discussing Babylonian mathematics and astronomy, for example, he scorns any reader who condemns the Babylonians for not formulating hypotheses to explain their observations of heavenly events. How would the reader determine the length of a solar year? No reference books allowed, the problem had to be solved by thought alone. By setting the reader such rhetorical questions, the Babylonians' ability to determine that the solar year was $365^1/_4$ days long without using instruments became all that more impressive. The same device is used at the end of the book when Westaway sets the reader 20 thoughtful and probing questions. Two contrasting questions, one based on bookwork and the other more diffuse and philosophical, will suffice to illustrate his purpose:

> What is an explosion? How long does it take a high explosive like T.N.T. to be converted into a gas? Explain why such a gas is so remarkably destructive, why its downward action is so violent, and why it does not expend its force upwards into the atmosphere.
>
> On being established in 1899, the Board of Education adopted the traditional views of the Science and Art Department of the Privy Council, which the Board succeeded, that physics and chemistry were the most suitable subjects of science for teaching in schools, views which still generally survive. To what extent do you consider this to be the cause of (1) the ignorance of, and (2) the lack of interest in, science by the average educated Englishman? If it is the cause, what is the remedy? If not the cause, what *is* the cause? (Westaway 1936, pp. 1037–1040)

73.7 Broadening Science Education

When looking back on his long career as an educator, Westaway was pleased by the way changes in teaching and educational practice had remoulded the minds of the younger generation. He was particularly struck by the way that the creation of sixth forms in secondary schools had led young people to become critical, well informed and opinionated. In one of his last, and perhaps oddest, books, Westaway encouraged intellectual debate among young people by providing raw materials for philosophical discussion and debate. He agreed completely with the views of the political historian Sir Ernest Barker who had written in *The Times*:

> At the end of a life spent in teaching, I am an educational anarchist so far as concerns the growth of true minds. When I find a true mind, I want to let it grow. Conscience used to make a coward of me, and I was once resolved to be a good tutor. Either I have lost my conscience, or it has acquired a finer edge. At any rate, I am now disposed to be very tender to the liberty of young minds. Their liberty includes their freedom from me. I insult them if I tell them first what to read – still more if I tell them what is 'the right view'. They need their own intellectual adventures. If they ask me to go with them, I am proud to be asked: if

> they ask me questions, I will tell them what I think – and I will add that I am far from being sure about it. (Barker 11 August 1937)[38]

Westaway's curiously titled *Obsessions and Convictions of the Human Intellect* (Westaway 1938a) from which this quotation comes contained a variety of informative and unbiased essays on subjects that were likely to interest young people between the ages of 16 and 25. Carefully excluding politics, the subjects ranged from astrology and alchemy, perpetual motion and the fourth dimension to questions about the nature of space and time, miracles, religious persecution down the ages and the concept of Hell ("atrocious" and "immoral"). Much of this curious work, which was aimed at providing a critical synoptic view of modern knowledge for pupils exposed to overspecialisation, was cannibalised (albeit reworked) from his other books. The first impression sold out immediately and was reprinted with a different, and probably more appropriate, title *Man's Search after Truth* (Westaway 1938b).[39] The book, which must have been an essential volume for school libraries, ends typically with a series of questions for the reader, but in this case they were questions that had all been suggested by young people when talking to Westaway.

The idea for *Appreciation of Beauty*, which Westaway published in 1939 soon after Chamberlain had negotiated "peace in our time" with Germany, came from the chapter on aesthetics that he had added to the third edition of *Scientific Method* in 1924. Echoing Robert Bridges' famous poem, dedicated to his wife Mary, on first reading it appears to address science students and scientists who may lack an appreciation of the arts, but a closer reading suggests that he had in mind a more general readership that felt it lacked an appreciation of "high culture" (Westaway 1939).[40] The book is, in fact, a vade mecum of culture offering guidance on how to understand and appreciate painting, sculpture, the history of art, architecture, ornament, arts and crafts, landscape and garden design, literature and music all underpinned by a philosophical discourse on aesthetics. In the final chapter, "What is meant by the beautiful", partly reworked from the third edition of his *Scientific Method* (1924), he concluded that Art "in the highest sense" involved "the reproduction of the phenomenon of nature" (e.g. sights and sounds), an "expression of the thoughts and emotions of the artist" and the embodiment of both these factors in "an external product like a painting, a statue, a cathedral, a piece of ornament, a garden, a poem, or a symphony" (Westaway 1939, p. 195). At the end of the day, beauty, he decided, had nothing to do with accepted canons of beauty or the consensus of experts. Nor could it be a Darwinian evolved sense that provided some kind of survival value. The appreciation of beauty was a form of communication from one human spirit to another, and because this communication was individual and personal, it was incapable of objective examination. Although the appreciation of beauty was undoubtedly a variable function of a person's education, experience, beliefs, traditions and

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[38] Sir Ernest Barker (1874–1960), as quoted in Westaway (1938a, p. xi)

[39] Pagination and content were identical to *Obsessions and Convictions* (Westaway 1938a). See the enthusiastic review in *Nature* (Anon 1938).

[40] Robert Bridges' final poem, *the Testament of Beauty*, had appeared in 1929.

customs, ultimately Westaway agreed with Robert Bridges that man's appreciation of nature and man-made art was God given – a conclusion he instantly qualified as an unverifiable hypothesis but one that gave him the greatest degree of personal satisfaction.[41]

The Appreciation of Beauty is fascinating in respect to what it reveals about Westaway's own tastes, as well as implying that he had studied art at the Royal College of Art in the 1880s where he had learned to draw accurately. In contrast to his progressive appreciation of modern science, he stands revealed as a very conservative connoisseur of painting. Good art had to be representational and to tell a story. Although well read on Victorian and Edwardian art criticism, Westaway completely ignored artistic developments since the pre-Raphaelites. Indeed, art since the Impressionists deserved to sink without trace. Not for him Kandinsky's appreciation of the spiritual nature of abstraction. The literary canon ended with Arnold Bennett. He detested jazz bands: "what front-rank musician has any real respect for a Jazz Band?" Live music was better than recorded music or music transmitted by wireless. Such opinions make him sound like an elderly schoolteacher whose fixed opinions had never altered. Despite this conservatism, Westaway's guide would have undoubtedly benefited a reader who wanted to improve their appreciation of high culture. Despite some "old-fogey" opinions and a decidedly deficient coverage of culture after about 1890, any reader would have received a lot of sensible advice of how to view pictures (e.g. where best to stand), how painters and sculptors achieved their optical effects, the need to know the Bible, classical myths and saint's lives to fully appreciate an artists' intentions and a contemporary guide to Britain's best museums and art galleries.

73.8 Westaway's Religious Views

Anyone reading Westaway's *Appreciation of Beauty* in isolation from his other writings might well assume that he held extremely orthodox religious views. They would be mistaken. There was a general tendency among thinkers to take stock of the human race after the cataclysmic First World War. Westaway was but one of many philosophers, theologians and scientists who, in the light of evolution and the emergence of modern physics and cosmology, published their views on the relationship between science and theology (Bowler 2001).[42] Like many other early twentieth-century scientists, theologians and philosophers, he was concerned to reintegrate science and religion by demonstrating that the Victorian forms of materialism no longer appealed to scientists. That being the case, the churches had to modernise and bring their teachings into line with contemporary science. *Science and Theology: Their Common Aims and Methods* appeared in 1920 and was

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[41] Westaway acknowledged that in writing the final chapter, he had received "great help and friendly criticism" from the philosopher and statesman, Arthur Balfour (1848–1930).

[42] Bowler did not notice Westaway's contribution to the debate.

reissued in an enlarged edition in 1934. It can be considered as an appendix to his *Scientific Method*.[43] His aim was to present the scientific developments of the past 50 years in layman's language and show their provisional nature. Because science was now a fundamental factor in human life and progress, he argued, any religious system had to find ways to accommodate it. Religious divisions were largely caused by a failure to accommodate new knowledge, and he appealed to Christians especially not to consider only their own doctrines as true and valid.

Reviewers were delighted by the book's directness and lucidity of style in dealing with matter, space and time, the genesis of the earth, the evolution of animal species, the antiquity of man and the emergence of life and consciousness (Sarton 1921; Anon 1920).[44] Westaway's conclusions were blunt: the belief that the same atoms of our bodies would reassemble on the day of judgement to form a human being was a pagan superstition; to express a belief in the resurrection of the body merely emphasised the material aspect of religion and was unnecessary; what really counted was a belief in the survival of personality. It followed that a belief in Christ's literal resurrection was unnecessary since what counted was the survival of Jesus' personality. Westaway accepted that the Bible had not been divinely inspired, but in accepting evolution he made it clear that it was meaningless if not teleological. A long, and erudite, section on controversies and heresies within the early church demonstrated how much theological clutter and primitivism needed to be eradicated from Christian doctrines. The "unbending institutionalism" of the church had to be eradicated. Westaway's convictions were clearly those of the Broad Church, an idealist philosophy and theistic belief:

> Theism has been aptly described as a systematized body of doctrine in which it is shown that an intelligent First Cause is the necessary and inevitable presupposition of experimental science, of reasoned knowledge, of aesthetics, of ethics, as well, of course, as of religion. If we want to explain our conceptions of the Real, the True, the Beautiful, or the Good, in each case alike we are inevitably driven to the conclusion that without an intelligent First Cause as a Beginning or Foundation, the whole of our scheme must dissolve and leave not a rack behind. (Westaway 1932, p. vii)

Once again he thanked Lord Rayleigh, who had died in June 1919, for his help with the manuscript, which was completed 2 months later. In a note added in proof, he observed that Einstein's "hypothesis" of relativity had been apparently verified – or, rather, just one of its consequences had. He remained doubtful, however, because he could not see how gravity acted in a void and he found the theory contradictory regarding the variability of time. However, by the time of the second, enlarged edition in 1932, Westaway had come to terms with relativity, stressing that we must carefully distinguish between *abstraction* which subtracts from observations and *hypotheses* (like relativity) that added to observations. The whole tendency of modern science, he noted in the light of quantum mechanics, was away from dogmatism and towards less certainty.

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[43] Indeed, chapter 1, "problems of philosophy", is largely a reprint of the final chapter of *Scientific Method* (Westaway 1912).

[44] Sarton (1921, p. 120) thought the book "very good indeed". The *Nature* reviewer (Anon 1920, p. 608) thought "the theology student is left without excuse".

73.9 Westaway's Personal Beliefs

What of the man himself? As a teacher, he was evidently both successful and something of a pioneer, using, for example, three-dimensional molecular models in the earliest days of his classroom career – namely, the 1880s:

> When I first taught organic chemistry… I bought … a gross of small wooden balls into which I screwed midget hooks. I wanted the boys [sic] to visualise molecules as three – dimensional things. (Westaway 1937b, p. 311)[45]

Westaway was not, of course, beguiled by this use of molecular models. Noting that his pupils "loved to play about with and interchange the coloured sub-groups of atoms", he asks:

> Which was the more immoral – to let the boys think that those 'molecules' were truly representative of nature, or to waste the school time in that way?

His answer was that "scientific laws are fundamental, and scientific hypotheses are useful, but scientific shams are an abomination".

It is clear from all of Westaway's writing that he was a notable scholar, with an unusual breadth of knowledge and an abiding commitment to understanding and promoting science as an endeavour dedicated to improving the sum of human happiness and well-being. The use and meaning of words were important to him, although he was no pedant, and in several of his writings, he exposes the ways in which convictions and prejudices hold sway in matters that should be governed by reason. His commentary upon the teaching of general science being promoted by the Science Masters' Association in the late 1930s is characteristically balanced. Although he welcomes the broadening of the science curriculum that the innovation represented, he commented that while "all reformers see pretty clearly the effects of action, … they seldom look far enough ahead to see the ultimate effects of a reaction", a warning that general science should not be reduced to serving up "juicy tit-bits all the year round" (Westaway 1937b).

He was also a man of his time, writing favourably of positive eugenics and sarcastically of antivivisectionists,[46] and although careful to deny gender bias and that he consistently referred to boys (rather than pupils) for convenience, the general impression one has from reading all of his books is that he did not think girls benefited much from courses in science. His professional duties and his writing inevitably meant that he worked to a strict timetable, but it is clear that he doted upon his daughter. He found time to teach her mathematics for two hours each Saturday morning to help her prepare for her secondary school entrance examination. The evidence is that both father and daughter found these sessions stimulating and

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[45] Such "glyptic" models had been first demonstrated by August Wilhelm Hofmann in the 1860s and could be purchased from instrument makers – to the disgust of the anti-atomist, Sir Benjamin Collins Brodie, professor of chemistry at the University of Oxford. See Brock (1967).

[46] "When the Anglo-Saxon or the Celt engages in a war of reason *v.* sentiment, sentiment almost invariably proves the winner" (Westaway 1936, p. 923).

enjoyable, Katherine describing them in later years as the highlight of her week (Kitchener 1981).[47] They were also undoubtedly successful, as Katherine found the mathematics component of the examination "too easy for words". Nevertheless, Westaway made it plain in his writings that he believed the average mathematical ability of girls was lower than that of boys and that their interest in mathematics was less. He even went so far as to suggest that the majority of girls did not need to study mathematics beyond the age of 13.

He was also a language purist, urging teachers to avoid the word "scientist" while admitting that the more correct term *sciencer* (analogous to astronomer) did not trip easily off the tongue,[48] and urged teachers to insist on the indicative mood when pupils wrote up their laboratory notes. As an inspector, he was highly regarded by his colleagues, while those he inspected found him astute in his judgement, constructive in his comments and unfailingly courteous in his dealings with people. He was unusually, perhaps, a welcome guest in many school staff rooms.

What, other than the deployment of science in war, prompted Westaway to place science "in the dock" and invite his readers to judge its guilt? Of what crime did science stand accused? Any answer to this latter question must, in part, be conjectural, but the "verdict" delivered by Westaway at the end of *Science in the Dock* and the text itself provide important clues. Reviewing, from the perspective of 1942, the position of science in relation to war, civilisation, education and religion in a rather muddled manner, Westaway ultimately leaves the verdict for the reader to decide. However, he suggests that a Scottish jury would bring in a verdict of "not proven" and that almost any jury would append to its verdict "the rider that science seems to be rather indifferent to the results of its work on the happiness of humanity". In addition, the jury would not improbably express the opinion that "not a few of the men who devote their lives to unearthing the secrets of nature really think less of the welfare of mankind than of their own enregistration on the roll of personal fame" (Westaway 1942a, p. 128).

Throughout his life, Westaway had tried to bridge the gap between science and the humanities, and, as noted above, he held firmly to the view that scientific knowledge should be directed towards the greater good of the human race. The collapse of humane values represented by the Second World War and its associated technology of destruction were thus a challenge to the ideas which Westaway had espoused and promised for many years. The publication of *Science in the Dock* in 1942 can be seen both as a personal exploration of the issues surrounding the social relations of science in the strained circumstances of a nation at war and as an attempt to reassert the importance of science as a humane endeavour. It can also be seen as an attempt by Westaway to expose the consequences of the early specialisation that marked English secondary education and to emphasise the need for breadth and balance. From the perspective of the early twenty-first century, however, one is also left to wonder about Westaway's attempt to reconcile his personal beliefs about science

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[47] For further information on Katherine Westaway, see Hunt (2004) and Godber and Hutchins (1982).

[48] Here he followed Gregory, *Nature's* editor. *Nature* did not use the word scientist until the 1940s.

and the Christian faith. Again, conjecture is inevitable, but his books on the aims and methods of science and theology suggest strongly that he accepted the notions of a first cause and a directing agency behind the natural phenomena that scientists made it their business to explore (Westaway 1920, Chap. 12).

Frederick William Westaway died from bladder cancer on 25 February 1946 at the age of 81. His personal papers have not survived. Unlike many of his colleagues in the inspectorate, he was never accorded an honour, nor did he have an entry in *Who's Who*, and the teaching press ignored his passing. His one and only obituary notice in the *Bedfordshire Times* simply recorded that his "kind and scholarly face will be missed".[49]

73.10 Conclusion: Westaway's Legacy

Westaway was but one of an army of HMIs whose support, criticisms and writings have contributed to science teaching over the past 150 years in ways that deserve fuller investigation by historians of education. We hope that this essay will encourage others to investigate the role of inspectors in encouraging and promoting science education.[50] In this essay we have highlighted the career of just one HMI whose contribution seems to have been of exceptional importance. Westaway was a somewhat unusual recruit to the inspectorate for most were Oxbridge graduates.[51] However, the range of his reading and expertise put him among the best graduates from Cambridge's mathematical and natural science tripos – the graduates he himself believed were the very best qualified to be excellent science and mathematics teachers. As Eric Holmyard commented, after reading Westaway's writings, a harassed schoolmaster will, after all, appreciate the usually dreaded attentions of an HMI (Holmyard 1929).

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[49] At the time of his death, the Westaways and their daughter were living in de Parys Road, Bedford, adjacent to Bedford School. At Probate in Oxford, 26 April 1946, his estate was valued at £4,604 (about £138,000 in today's buying power) and willed solely to his daughter, presumably because of his wife's incapacity. Mary Westaway died on 9 March 1947. All three Westaways are buried in the churchyard of All Saints, Renhold, where the family evidently worshipped.

[50] However, HMI reports of science lessons can be disappointing as source material. HMI visits were infrequent and often focused on different aspects of a school's work, making comparisons difficult. For a guide, see Morton (1997).

[51] For example, Charles Thomas Whitmell (1849–1920), BSc (London), NST (Cambridge), taught chemistry and physics at Tonbridge School before joining the inspectorate in 1879 serving in Cardiff (1879–1887) and at Leeds until retirement in 1910; Frederic W. H. Myers (1843–1901) became an HMI in 1872 after teaching classics at Cambridge; Francis Bernard Stead (1873–1954), a close friend of the Westaways, had worked at Plymouth's Marine Biology Association before joining the inspectorate; and Thomas W. Danby (1840–1924), NST (Cambridge), assisted the chemist George Liveing before becoming chief inspector of schools for south-east England. For some amusing reminiscences of inspection in the second half of the nineteenth century, see Sneyd-Kinnersley, E. M. (1908).

But what, it might be asked, is the relevance of Westaway's writing to school science teaching today, given the profound changes in the social context of both science and religion?[52] Part of the answer lies in the fact that many of the issues that Westaway addressed have arguably become more, rather than less, important and that some of his arguments, lucidly and eloquently developed and expressed, continue to offer a challenge to the contemporary mind. Beyond this, some of Westaway's writing about science and education sets a standard that others might seek to follow, notwithstanding the changes that have taken place in the last half century in our understanding of the history and philosophy of science. Ultimately, however, reading Westaway forces the reader to ask questions about the educational function of science, questions that seem to be urgently in need of answers as school science education is increasingly cast in an instrumental mode, serving economic rather than humane ends.

At a time when serious doubts are again being expressed about whether practical work and experimentation should play an essential (but expensive) role in schools, Westaway's arguments are well worth reading again.[53] We can also take to heart Westaway's expectation (and challenge) that

> When a boy leaves school, he should have been so taught and be so informed that he is able to take an intelligent interest in all scientific, technical, and industrial developments. He should be able to turn up technical reports, and obtain at least an intelligent general grasp of their contents. He should be able to discuss in a council chamber the pros and cons of proposed new applications to industrial processes. In short, the former secondary school boy should be the disseminator of new knowledge and the intelligent adviser of the community. (Westaway 1929, pp. 385–386)

Because of the way that the sociology of science has transformed approaches to the history and philosophy of science since the 1960s, Westaway's *Scientific Method* is now only of historical interest. Similarly, his pioneering *Endless Quest* has been superseded by a more nuanced and critical approach to the history of science – though it has to be said that no historian has been able to provide a better encyclopaedic and illustrated guide for teachers on how scientific achievements were brought about. Its message, taken from Westaway's grasp of philosophy, that despite the "passing of dogmatism" there is no reason to suppose "that what is mathematically describable is ultimately real, and the only reality", is one that all teachers should reflect upon. Finally, despite worldwide cultural differences and national varieties of syllabuses and curricula, his *Science Teaching* and *Craftsmanship in the Teaching of Mathematics* remain inspirational and illuminating reading for both novices and experienced teachers.

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[52] For Westaway's continuing relevance in an American context, see Keller and Keller (2005) and the electronic blog at http://www.smartscience.net. See also Matthews (1998).

[53] See, for example, Taber (2011). The issue is also highlighted by the REACH legislation on the safety of chemicals.

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Chapter 74
E. J. Holmyard and the Historical Approach to Science Teaching

Edgar W. Jenkins

74.1 Introduction

Eric John Holmyard (1891–1959)[1] was a scholar and schoolmaster and a significant figure in the history of science and in science education during the first half of the twentieth century. Although his research into alchemy is well known to historians of science interested in early chemistry, his historical approach to science teaching has received much less attention from the science education community, the study by Kinsman (1985) being a conspicuous but unpublished exception.

Born in 1891 in Midsomer Norton, Somerset, in the West of England, his father, Isaac Berrow Holmyard, was a schoolteacher in a national school, i.e. an elementary school set up by the National Society for Promoting the Education of the Poor in the Principles of the Established Church. After attending Sexey's School in Bruton, Holmyard went up to Sidney Sussex College, Cambridge, to read history and science. He graduated in both these disciplines with a first in natural science and a second in part two of the history Tripos. After working as a Board of Agriculture Research Fellow at Rothamsted Experimental Station, he taught briefly at Bristol Grammar School and Marlborough College before becoming head of science[2] at Clifton College in Bristol in 1919.

Holmyard entered the teaching profession at a time when schooling in England was undergoing a period of significant change. The Education Act of 1902 had created Local Education Authorities (LEAs) with responsibility for publicly funded

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[1] Although Holmyard used both his initials in all his publications, he preferred the name John to Eric (McKie 1960).

[2] The terms of Holmyard's appointment were unusual in that he was relieved of all out-of-school duties and, until 1936, lived in Clevedon and travelled daily to Clifton (Kinsman 1985; Williams 2002). His appointment at Rothamsted reflected his study of biology in Part 1 of the Tripos examination.

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elementary and secondary schools, with a small proportion of pupils from the former selected to enter the latter on the basis of an examination at the age of 11. Secondary, i.e. grammar, schools under the control of the LEAs were quickly established across the country, and many chose to organise themselves on the basis commonly associated with the public (i.e. private) schools, creating houses, appointing prefects and promoting competitive sporting activities. However, unlike the public schools, the curriculum of the LEA grammar schools was governed by Regulations issued annually by the Board of Education which required the teaching of both practical and theoretical science. Despite the experience of pioneering schools like Clifton College, much remained to be learnt about best to organise and teach science in the grant-aided secondary schools, 1,027 of which were established by 1914 (Simon 1974, p. 363). There was therefore much debate about the order and manner in which topics should be presented and taught and about the roles to be accorded to expository teaching, teacher demonstration and laboratory work conducted by pupils (Fowles 1937; Jenkins 1979). For reasons that are discussed below, that debate became particularly significant in the years following the end of the First World War.

This essay reviews Holmyard's contribution to the historical method of science teaching and comments upon why the history of science has featured so prominently in the history of school science education.

74.2 The Historical Method of Teaching

Founded in 1862 under the headmastership of John Percival, Bishop of Hereford, Clifton College was somewhat unusual among the 'public' schools in England in the mid-nineteenth century in that it 'took science seriously' (Brock 1996, p. 373). It was a legacy upon which Holmyard was able to build. Under his leadership, the College acquired an astonishing collection of manuscripts and first editions of scientific works for its new library[3] and established an outstanding reputation for its science teaching. According to the author of the relevant entry in the *Dictionary of National Biography*, 'Under his guidance, Clifton established a reputation for science probably unequalled, and certainly not surpassed, by any other British school' (Williams 2002; see also Williams 2004).

Holmyard was an enthusiastic advocate of a historical approach to the teaching of chemistry which helped pupils to learn how discoveries were made and, more particularly, to familiarise themselves with the ideas in the minds of the researchers

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[3] The Library, known as the Stone Library, was built with funds from Old Cliftonians. The first editions purchased for the library included Newton's *Opticks* and Darwin's *On the Origin of Species*. Clifton College also purchased material at Sotheby's 1936 sale of Newtoniana. Opened in 1927, Holmyard was justifiably proud of the new Science Library which he believed had 'no rival in any school in the world' (Holmyard, writing in the *Cliftonian* of June 1927 and quoted in Williams 2002, p. 204).

and to understand the methods by which they had overcome difficulties. His advocacy reflected a deep scholarly interest in the early history of chemistry, notably in alchemy, at a time when the history of science was becoming established as a distinct academic discipline: the journal *ISIS*, for example, was founded by George Sarton in 1912 and Department for the History and Methods of Science Department at University College London in 1921. Holmyard taught himself Arabic and acquired a good working knowledge of Hebrew, skills which enabled him to edit several important Islamic alchemical texts and to shed light on the work of early alchemists, research for which the University of Bristol awarded him a D. Litt. in 1928. He was in demand as a reviewer for several journals, including *The Journal of the Royal Asiatic Society*, reviewing publications in French and German as well as English. He served (1947–1950) as a vice-president of the newly formed British Society for the History of Science and later as an ordinary member of its council (1953–1954) and as chairman of the Society for the Study of Alchemy and Early Chemistry. He was also a corresponding member of L'Académie Internationale de l'Histoire des Sciences.

In a detailed review of approaches that had been recommended or used to teach chemistry, the schoolmaster George Fowles[4] suggested that a historical approach could be biographical, recapitulatory or be based upon the evolution of scientific ideas (Fowles 1937, pp. 511–18). The first of these relied on the biographies or published diaries of famous scientists and was sometimes coupled with the anecdotal in an attempt to relate the research of individual scientists to wider social, economic or political concerns. The work of Haber on nitrogen fixation is an obvious example. The recapitulatory approach was adopted by Perkin and Lean in their *Introduction to the Study of Chemistry*, first published in 1896 (Perkin and Lean 1896).[5] Convinced that 'the order in which problems have presented themselves to successive generations is the order in which they may be most naturally presented to the individual', they claimed that many of the chapters had been worked through by elementary students in the laboratories of Owens College, later the University of Manchester (Perkin and Lean*op.cit.*, pp. vii-viii and xi). However, the recapitulatory approach does not seem to have been widely used, partly because it involved devoting time to teaching ideas and processes that had long been superseded or could be taught much more effectively and economically in other ways. Fowles, writing a generation later, suggested (*op.cit.,* p. 515) that the approach could work well only when controversy and blind alleys did not significantly interrupt the presentation of the historical narrative. His overall judgement (*op.cit.*, p. 514) was that the 'much vaunted' recapitulatory method had 'never been faithfully carried out in practice'.

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[4] For Fowles, see Jenkins (2000). Fowles was a close friend for over thirty years of John Bradley who regarded him as his 'friend and mentor' and his book as 'indispensable to the teacher of chemistry' (Bradley 1988, p. 2).

[5] Perkin and Lean's book held 'a position of honour' on the bookshelves of John Bradley who was introduced to it by his teacher at Archbishop Holgate's Grammar School in York, Henry Worth (1870–1949). Bradley was a distinguished teacher and teacher educator who was much influenced by the writings of Mach and who taught at Christ's Hospital where he met H. E. Armstrong (Bradley *op.cit.*).

The evolutionary approach was intended to help students understand the personal, intellectual, professional, economic and social factors that characterised the historical path towards the current understanding of natural phenomena. The value of this approach lay in countering the view that former ideas were simply the absurd outcomes of prejudice or mistaken judgement and in understanding the qualified degree of confidence that should be placed in more contemporary explanations of natural phenomena.

> We like to be thought devotees of truth uninfluenced by prejudice, as open-minded and serene students of nature, free from suppositions and welcoming every fact that comes within our ken… When the errors of our predecessors are forced upon our notice we may lament them or be amused or may seek to excuse them, but that the same lamentations and excuses may some day have to be made for us we can hardly think possible. (Lodge 1925, p. i)

Although he never referred to it as such, it is this evolutionary approach that most aptly describes Holmyard's historical method of teaching chemistry. He argued his case at a vacation course for science teachers held in Oxford in the summer of 1924[6] and in an article published in the same year in *The School Science Review*, the journal of the Science Masters' Association, an organisation of which he was a committee member and, a year later, president (Holmyard 1924a, pp. 227–33).

He began by addressing the widely held belief that school chemistry could be taught in two ways, depending upon whether the students would eventually become chemists or not. For the former group, the emphasis was placed on the grammar and syntax of the discipline, on learning the rudiments of canonical chemistry. For the latter, the 'chemistry of everyday life' was usually accorded priority. For Holmyard, this distinction was 'a grave fallacy' that rested upon 'the fundamental misconception that chemistry is a craft, when essentially it is a philosophy' (*ibid.,* p. 227). He was thus scornful of the enduring educational merits of snippets of chemical knowledge that enabled someone later in life to solve an acrostic in a daily newspaper or to understand that 'the 'will o'-the-wisp' is caused by the combustion of marsh gas…produced by the action of little insects, called germs (*sic*), upon dead plants' (p. 228). He does not, however, suggest that knowledge of this kind is to be regarded as having no value. On the contrary,

> …how often, after having cut myself while shaving, have I thanked Heaven that my chemical education had been carried to such a degree of perfection that I knew a trivalent cation was especially effective in the coagulation of colloids!

He then adds, in a remarkable sentence, that

> Merely to have rubbed on alum in an unintelligent way would have robbed the operation of all its ecstasy, and I should not have felt that piquant sense of superiority over my daily companion in the train, Lucas, the stock-broker, who is so ignorant that he doesn't even know the empirical formula for the starch in his own collars! (p. 229)

This is one of several examples in Holmyard's article of what he called 'levity', the intended irony of which could all too easily be misunderstood. However, all the

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[6] Holmyard's contribution to the course was subsequently published as a pamphlet entitled *The Teaching of Science* (Holmyard 1924b).

examples served to introduce his main argument, namely, that the chief value of chemical education stemmed from the precise, logical and formal character of the discipline, not from its personal or economic utility. He then went on to address the question why chemistry has an educational advantage over other disciplines, such as mathematics, which can be characterised in similar terms. His answer was that chemistry appeals both to intellect and to emotion and is not a 'cold, discarnate scheme of mental gymnastics' (p. 231).

Claiming that 'the immediate [favourable] reaction to biographical details is a universally recognized trait of youthful psychology', Holmyard asked who 'could fail to be stirred by accounts of Pasteur's romantic search for *l*-tartaric acid, of Priestley's discovery of oxygen, of Moissan's isolation of fluorine?' He claimed that he had successfully used his historical approach with his own students at Clifton.

> Personally, I have never found any difficulty in getting a boy to 'believe' in the 'truth' of the sulphur-mercury theory of metals, to get him to abandon it for phlogiston theory, or to abandon this in turn for the oxygen theory, with the result that the last theory is regarded by him in a very different way from that in which a boy looks at it who has had it taught to him dogmatically (Holmyard 1924a, p. 232).

In addition to arguing for, and illustrating, Holmyard's historical approach to teaching chemistry, his article in *The School Science Review* also provides some insight into his understanding of the philosophy of chemistry. It is clear that, for Holmyard, this understanding did more than support his historical approach to chemical education: it provided its underpinning rationale. Only by adopting such an approach could students be led to understand that 'Science in general and chemistry in particular are but conceptual schemes which must always bear an unknown relation to the precepts they correlate' (p. 231). Elsewhere, he invokes a biological analogy to express his view of the history of science.

> '…the theory of evolution is applicable to the development of science no less than to the world of birds, beasts and flowers. (Holmyard 1925c, preface)

For Holmyard, scientific knowledge is to be regarded as essentially pragmatic, not connected with questions about the nature of reality, and as free of any special ontological assumptions and untainted by narrow questions of economic benefit. For the anonymous reviewer of his pamphlet, *The Teaching of Science*,

> Mr Holmyard is not concerned with a universe of absolute truth and rigid law, but with a humble and tentative hold on the precarious hypothesis of an external world. (SSR 1925a, p. 266)[7]

Almost twenty years later, Holmyard wrote that

> Reality, if it is to be discussed at all, must for the present be discussed as a philosophical problem, and the scientist as a scientist need not adventure into such regions…a theory is merely a conceptual model of perceptual facts…a tool rather than a creed. (Holmyard 1944, p. 126)

Holmyard's concern to put some distance between the discipline of chemistry and its uses brought him into conflict with his fellow members of the Science Masters' Association (Layton 1984, p. 203).

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[7] Unless otherwise indicated, all reviewers were anonymous.

> …any scheme that sets out to be utilitarian, in the narrow sense of the word, or merely ‘interesting’ is blatantly immoral, and rightly deserves the censure it invites. (Holmyard 1924a, p. 230)

He therefore had no time for the courses of ‘General Science’ which the Association was strongly promoting in the interests of ‘science for all’.

> I am…with those who cry ‘Science for All’ but I would add ‘and Dabbling Science for Nobody’. I have no sympathy with kindergarten schemes of ‘general science’. [They are] fallacious and shallow…. (Holmyard 1924a, p. 229)

If students of science are to be helped towards what Holmyard described as the ‘truth’, only the historical method of teaching could bring this about.

> The historical method is not, I believe, one of several equally good alternative schemes of teaching chemistry in schools: it is the only method which will effectively produce all the results at which it is at once our privilege and duty to aim (*ibid.*).

In addition, it was only the historical method that could enable students to appreciate to the full ‘the serene joys of the intellectual life’ and steer school science education in a much needed new direction.

> …the main result of the teaching of science in our schools has been to accelerate the spread of that contempt for and indifference to ethical, moral and aesthetic values, and to spiritual and religious truth…perhaps the chief characteristic of our civilisation. (Holmyard 1925b, p. 490)

Nothing less than a fully worked out historical approach could bring this about and he cautioned that

> Many teachers, in all good faith, imagine that they are adopting this method [of teaching] if they drag in a few biographical details…fascinating as it may be, and valuable as it certainly is, in stimulating the child’s interest and attention, it does not by itself constitute the historical method. (*ibid.,* p. 492)

Holmyard’s views were supported by J. W. Mellor, FRS, author of several textbooks and of a landmark multivolume *Comprehensive Treatise on Inorganic and Theoretical Chemistry.* Asserting that ‘every teacher now recognises that it is a sheer waste of time to introduce many abstract ideas into an elementary science course without a previous survey of the facts from which the generalizations can be derived’, Mellor[8] argued that ‘in most cases the historical mode of treatment is correct, because the generalizations have usually developed from contemplation of the facts’ (Mellor 1932, preface).

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[8] Joseph William Mellor CBE, FRS (1869–1938) was born in Lindley, a suburb of Huddersfield in the West Riding of Yorkshire, but left for New Zealand at the age of 10. He returned to England in 1899 to take up an appointment as chemist to the Pottery Manufacturers Federation in Newcastle – under Lyme. Mellor soon established himself as a researcher of international standing, working on the structure and properties of ceramic materials. In 1934, he was appointed director of the new laboratories of the British Refractories Research Association, named in his honour. In addition to his monumental multivolume treatise on inorganic chemistry, he was a highly competent mathematician, and his book on mathematics for chemists and physicists became widely used (Mellor 1902).

74.3 Criticism of the Historical Approach

Holmyard will have been well aware that the historical approach to teaching science also had its critics. The pioneering Cambridge chemist, Ida Freund, author of a seminal book, *The Study of Chemical Composition* (Freund 1904), had little time for such an approach. She fully understood the importance of understanding the history of a scientific discipline and had written a prize-winning historical study of the constitution of matter, some of which almost certainly influenced the approach taken in her 1904 book. Nonetheless, to those who wanted students to retrace the paths by which scientific discoveries had been made, she replied that

> Even if such a plan could be consistently adhered to …it is better to take the shorter way to the goal, this being after all a way by which the discovery might have been made. (Freund 1904, quoted in Fowles, *op.cit.*¸ p. 513)

In 1929, in a book entitled *Science Teaching: What it was – What It Is – What it Might Be*, F. W. Westaway[9] warned that

> if the historical method is to be adopted, the general method of the history teacher must be followed…What is the point of discussing Roger Bacon and his work unless a boy first understands something of the spirit of mediaevalism – any person who attempted to unravel nature's secrets must be an emissary of Satan himself, and punished accordingly. (Westaway 1929, p. 32)

For Westaway, this condition meant that 'teaching in accordance with historical sequence' could not 'be recommended for subjects usually taught up to the fifth form [i.e. about the age of 16] –physics, chemistry and biology' (*idem.*). He was cautious of the slow progress that the historical method allowed, advising that 'it simply does not pay to spend a whole lesson over, say, the phlogiston hypothesis'. Even so, he felt that some aspects of school science, such as astronomy, were well suited to being 'developed historically and to great advantage' (*ibid.* p. 31).

In 1930, the historical method and Holmyard in particular were the subject of criticism by H. H. Cawthorne. A graduate of King's College London, Cawthorne had worked in teacher education at the University College of the South West, Exeter, before taking up a post at Firth Park secondary school in Sheffield. In his *Science in Education* (Cawthorne 1930), he devoted a whole chapter (pp. 66–75) to the historical method which he is careful to distinguish from a more narrowly biographical approach to school science teaching. While acknowledging that the historical method of teaching has merits, including preventing a 'dogmatic treatment of present-day thought', Cawthorne challenged the notion that the standpoints of the student and of the scientific discoverer are roughly the same. He concluded that it was not necessary for students to 'wade through all the mire and clay of controversy' which have, at times, been obstacles to the progress of science. His advice to teachers was that in order to prevent confusing students or using excessive time, it was necessary to 'short-circuit' some parts of the full historical argument. As a further obstacle to

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[9] For Westaway, see Jenkins (2001) and Brock and Jenkins in this volume.

teaching in the way advocated by Holmyard, he reminded his readers that the mind of the mid-twentieth-century student was packed with ‘many odd scraps of information which the most fertile imagination of the seventeenth century philosopher could never have supplied’. He offered the example of liquid air, a concept familiar to many of his students but which would have nonplussed the early members of The Royal Society (*ibid.,* p. 75). Today, when scientific ideas and explanations are widely available in museums and the print and broadcast media, Cawthorne’s point is even more telling.

For another schoolmaster, Fowles, writing in 1937, while the historical method of teaching chemistry was ‘attractive in theory’ and ‘appealed to the philosophically minded…few had drawn up a scheme or work or attempted to put the method in practice’ (Fowles *op.cit.*, p. 513). He wondered whether students, helped by their teacher to understand that a theory was no longer tenable, might be puzzled why it was retained in the face of new experimental evidence by ‘men of the depth of intellect of Priestley and Cavendish’. He asked who, ‘Notwithstanding the simplicity of the experiments …decomposes mercuric oxide with the heat of the sun concentrated by means of a 12-inch lens…when oxygen is much more easily prepared by other means?’ (*op.cit.*, p. 514). His judgement on the historical method was that ‘one is constrained to believe that the students have done little more than accept the belief of the teacher’ (p. 517).

However, there was more to Holmyard’s advocacy of the historical approach to science education than the insights it could offer into what today is referred to as ‘the nature of science’. It also added a much-needed human dimension to the subject.

> If Science is to retain the honourable place it has won in the educational system of this country…we shall have to recognise that is the greatest of the “humanities”, and deliberately abandon the so called “utilitarian” standpoint. (Holmyard 1922, preface)

It is interesting to place Holmyard’s rejection of the ‘utilitarian standpoint’ alongside the view of Harold Hartley, FRS,[10] a distinguished physical chemist and contemporary who saw science

> …not merely as an academic subject- nor only as a basis for applied technological development but as a great cultural adventure that comprised both of these: as an historical sequence, having its nourishing roots in the past and its growing branches thrusting constantly into the future. (Ogston 1972, p. 366)

Holmyard was by no means without support in seeking to present science as a humanity. Turner, in her account of the history of science teaching in England, came to the conclusion that

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[10] Sir Harold Brewer Hartley, C.H., FRS, was taught chemistry by H. B. Baker at Dulwich College in London who encouraged him to read and buy old chemistry books. Hartley went on to Balliol College, Oxford, to develop a lifelong interest in the history of the discipline. During his long life he held a variety of academic, business and industrial appointments. He secured the Lewis Evans collection of scientific instruments for the University of Oxford and was a frequent contributor of historical articles, especially about nineteenth-century English chemists, to the *Notes and Records of the Royal Society* of which he was the editor for eighteen years. The preface to his *Studies in the History of Chemistry* (Hartley 1971) reveals that the book was commissioned nearly 70 years earlier!

> …if science teaching is to mean anything more than the acquisition of a few tags of knowledge and a certain skill in manipulation we must accord it a place among the humanities… The human side is perhaps best introduced by a carefully selected historical treatment. (Turner 1927, p. 191)

In the aftermath of the First World War in which chemistry had played such a massive and destructive role, recasting science as a humane study was widely regarded as necessary and it helps to explain why, despite the practical difficulties of implementing Holmyard's ideas, the incorporation of at least some elements of the history of science in school curricula received a broadly sympathetic hearing.

> How necessary Science is in War…we have learnt at a great price. How it contributes to the prosperity of industries and trade, all are ready to admit. How valuable it may be in training the judgement, stirring the imagination and in cultivating a spirit of reverence, few have yet accepted in full faith. (Natural Science in Education 1918, para.4)

Reaction to the role of science in the First World War was not the only influence at work in seeking to 'humanise' school science. During the 'battle of the books' that had broken out in the middle of the First World War, supporters of a classical education had reacted vigorously to the claims of a self-styled 'Neglect of Science Committee' established to promote science education and research (Jenkins 1979). Ramsay MacDonald told the House of Commons that this committee was 'practically telling us to clear the humanities out of our schools' (Hansard 1916, col. 906), and an editorial in *Blackwood's Magazine* in 1916 described the 'ferocious attack on the humanities as evidence of the 'unbalanced men of science who wish to kill off all learning other than their own'. Those who had praised German scientific and technological achievements before the war now found their own evidence being used against them.

The clash between the scientific and classical contributions to education was not confined to the UK, and the battle was not always conducted in terms conducive to effecting a rapprochement. In the USA, for example, one commentator opined that 'Largely without the benefit of the Classics, it is not to be expected that [the ordinary scientist] should know what the Humanists are saying or realize his faults' (Glaser 1924, p. 30). In the UK, the distinguished Wykehamist classical scholar and educator, Sir Richard Livingstone, claimed in his *Defence of a Classical Education* that the fundamental weakness in science as a vehicle of a liberal education was that

> …[science] hardly tells us anything about man. The man who is our friend, enemy, kinsman, partner, colleague, with whom we live and [have our] business, who governs or is governed by us [never once] comes within our view. (Livingstone 1916, pp. 30–31)

It is clear that Holmyard, who regarded science as an integral part of culture, would have rejected Livingstone's claim that science 'hardly tells us anything about man'. It is equally clear, as noted above, that Holmyard thought science as it had been taught had accelerated a contempt for, and an indifference to, ethical, moral and aesthetic values and to spiritual and religious truth. It is noteworthy therefore that the Foreword to his *Inorganic Chemistry*, first published in 1922, was written, presumably at Holmyard's invitation, by a leading classical scholar, Cyril Norwood. Holmyard would have encountered Norwood when the latter served as headmaster at Bristol Grammar School (1906–1916) and Marlborough College (1917–1925), respectively, before moving on to the headship of Harrow (1926–1934). Norwood has been described as the 'quintessential insider of English education in the first half of the twentieth century' (McCulloch 2006, p. 55; see also McCulloch 1991). He was an influential source of government advice, eventually being knighted for his services to education. In 1929, Norwood published *The English Tradition of Education* which offered a deeply complacent and conservative view of the past, a past that was closely linked to the teaching of the classics in the English public and endowed grammar schools. In his Foreword to Holmyard's book, Norwood is deeply critical of the system of Higher Grade Schools that had developed in England during the last quarter of the nineteenth century (Vlaeminke 2000). Funded for the most part by grants from the Department of Science and Art, these locally controlled post-elementary schools attached much greater importance to science than many public and endowed grammar schools and provided an 'alternative' secondary education in all but name.[11] Norwood claimed that the teaching in these schools had been 'one sided' and excessively formal and that it had taken the Great War to forcibly remind the nation that things were not well. He saw Holmyard's *Inorganic Chemistry* as offering a way forward.

> [The author] knows how to teach with breadth and without exclusiveness. Its pages give information and provoke curiosity: at many points they suggest that there are other realms of knowledge of a quite different sort. (Norwood 1922, p. *v*)

It was an endorsement that one can safely assume met with Holmyard's approval.

When the newly formed Science Masters' Association held its annual meeting in 1920, there was widespread agreement that school science courses needed to be both broadened and 'humanised', although there was much less confidence about how this could be achieved. For some, the way forward lay with a broad course of General Science which 'furnished the mind' and 'gave some knowledge of the world in which we live' (Tilden 1919, p. 12). For others, it was essential to capture the spirit and romance of scientific endeavour by incorporating a biographical element into school science education, 'the history of men and the setting forth of noble objects of action' (Sadler 1909, p. *xi*). For yet others, it was Holmyard's evolutionary approach to the history of scientific ideas, or at least some aspects of it, that seemed to have most to commend it.

Unsurprisingly, each of these possible directions for science education reform presented difficulties. Despite the success that Holmyard claimed he had achieved with his own students, his historical method was the subject of ongoing debate and critical commentary throughout the interwar years. Interestingly, there appears to be no evidence that he sought to reply to his critics by, for example, writing for *The School Science Review* or publishing a more detailed and practical account of

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[11] See McCulloch (1984). The Higher Grade Schools are seen by some historians as constituting an 'alternative road' to that represented by the traditional grammar school curriculum. They were swept away by a series of legislative changes between 1899 and 1902, although some re-emerged as secondary, i.e. grammar, schools under the control of newly created Local Education Authorities. See Vlaeminke (2000).

his historical method to which science teachers could refer.[12] Fowles (*op.cit.*, *p.* 517) expressed some admiration for Holmyard's success in 'getting a young class to grasp the doctrine of phlogiston' but questioned 'how little of elementary chemistry' could be taught along the lines advocated by Holmyard and how far it was expedient, and actually possible in the time usually available, to secure topical development along such lines. Although it is impossible to be sure how widely Holmyard's approach to school science was adopted, it seems clear that for most science teachers it presented formidable, even insuperable, difficulties. Few teachers could command the knowledge of the history of chemistry or physics required to take students back and immerse them in the period under consideration, and there is little evidence to suggest that the obstacles identified by Cawthorne, Fowles and others were successfully overcome. In a book written 'for teachers and training college students', John Brown, a school inspector for the London County Council, could do no more than advise that 'with older pupils, the study of a certain amount of *historical development'* of the subject will prove profitable (Brown 1925, pp. 45–6).

74.4 'Ships' Surgeons Are Always Truthful!'

While Holmyard's historical method may have failed to find widespread favour among his science teaching colleagues, his scholarly achievements in the history of science were able to find generous expression in his large number of school science textbooks. There are likely to be few, if any, chemistry teachers of an older generation familiar with the English education system who will not be able to recall his name. Some may even be familiar with the above quotation – of which more below.

Holmyard was a prolific author. Throughout the interwar years in particular, publications concerning the history of science appeared alongside a steady stream of school science textbooks. The British Library Integrated Catalogue lists over a hundred entries for Holmyard (although this number includes several different editions or reprints of the same book) and a large proportion of the entries relates to works published between 1922 and 1939. The 1920s alone produced *Chemistry to the Time of Dalton,* published in 1925, two translations of Avicenna (1925c) and

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[12] A comparison with H. E. Armstrong is of some interest. Both men sought to give students an insight into how scientific knowledge was obtained and validated, although Armstrong's emphasis on the practical teaching of 'scientific method' could not be more different from Holmyard's more complex, nuanced historical approach. Unlike Holmyard, Armstrong was a vigorous promoter of his *virus heuristicum Armstrongii* and even compiled a book setting out his ideas (Armstrong 1903), although its lack of coherence made this a less useful advocate of his cause than it might have been. See, for example, Browne (1954/1966) and Brock (1973). For both heurism and the historical method of science teaching, science teachers were undoubtedly the weakest point. As individuals, Holmyard was described as a 'quiet' and 'tolerant' man (McKie 1960, p. 5), as having 'a modest and retiring disposition' (*The Times*, October 15, 1959) and an 'imperturbability of temper' (Singer 1959, p. 17), descriptions that could never be applied to the hot-tempered Armstrong who 'always made one think [but] was fond of saying that very few…were capable of doing so' (Hartley 1971, p. 195). For Holmyard's views on heurism, see Holmyard (1925b, p. 490).

a critical and important translation of the Arabic works of Jâbir Ibn Hayyân (1928a), a year that also saw the publication of *The Great Chemists*. The same decade also witnessed the first publication of over a dozen school science textbooks, some of which were reprinted or revised and remained in use for at least the next thirty years.

Some of Holmyard's textbooks were phenomenally successful. His *Elementary Chemistry*, first published in 1925, was reprinted eleven times by 1933, eventually selling over half a million copies worldwide (Holmyard 1925a). Even today, when chemistry has undergone so many profound changes, it remains a remarkably interesting book. The frontispiece is an extract of a dialogue between master and pupil from *Ye Booke of Allchimye* written in the twelfth century, its first two chapters address the questions of what chemistry is and how it arose and the book ends with biographical notes on some famous chemists. Few, if any, modern elementary school chemistry texts begin by introducing pupils to the complex, multicultural origins of the discipline, provide illustrations of Arabic chemical operations, review the multiple uses and benefits of chemistry and explain how chemistry itself came to be so called. While what follows these opening chapters is a well-ordered presentation of familiar information about the occurrence, preparation, properties and uses of the chemical elements and their compounds, few readers would have failed to find something of interest even when this was incidental to the main text. For one reviewer, the book revealed Holmyard's 'adventurous and at once recognizable style' along with his 'store of humorous delights on chemistry' (*J. Chem. Ind.* 1934, p. 882). His *Chemistry for Beginners* prompted another reviewer to comment that 'Mr Holmyard's books always please us', adding that 'he had the rare gift of writing so as to interest the young' (*J. Chem. Ind.* 1931, p. 146).

No less successful as a publication and equally well received by the book's reviewers was his *A Higher School Certificate Inorganic Chemistry* which appeared in 1939. For one reviewer, the reading and rereading of this book had been 'sheer delight', adding that it was 'not possible to write of it save in terms which appear exaggerated'. For the journal *Nature*, it was simply 'excellent'. Following the replacement in 1951 of the system of School Certificate Examinations by the O- and A-level examinations of the GCE, Holmyard collaborated with W. G. Palmer[13] to produce in 1952 a revised edition, entitled *A Higher School Inorganic Chemistry.* The above reference to the truthfulness of ships' surgeons will be found on page 272 of the first edition and

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[13] Palmer was a Fellow of St. John's College, Cambridge, when Bradley (see note 5) was an undergraduate and gave him 'a taste for the history of chemistry' (Bradley *op.cit.*, p. 1). Holmyard also collaborated with Frederick Arthur Philbrick to produce *A Textbook of Theoretical and Inorganic Chemistry* (Philbrick and Holmyard 1956). Philbrick died at a comparatively early age. Holmyard may have felt the need for collaboration since he had given up his post at Clifton College in 1940 when the school was evacuated to the relative safety of Bude in Cornwall. Although Philbrick is identified as the lead author, the book 'was mostly Holmyard, Philbrick having been responsible for bringing later editions up to date' (Francis 2004, p. 15).

Holmyard subsequently took up the editorship of the magazine *Endeavour*. Published by ICI, the magazine sought to publicise British scientific and technological achievements. Intended as a war time publication, it proved so successful under his editorship that it continued after the war ended when it was produced in five languages (English, French, German, Italian and Spanish). Holmyard remained its editor until 1954. His obituary was published in *Endeavour*, 73, January 1960.

page 275 of the revised volume. Referring to the salvaging of 30 tons of mercury from a Spanish wreck off Cadiz by HMS Triumph in 1810, the reader is told that the symptoms of mercury poisoning quickly became evident among the crew and livestock of the salvage vessel. Lest any should doubt the word of the ship's surgeon, quoted in the text, that he 'had seen mice come into the ward-room, leap up to some height, and fall dead on the deck', the reader is referred in a footnote to the quotation cited above. In a discussion of the colloidal state on page 147 of the earlier volume, the poet Keats is invoked to describe a gel as 'soother than the creamy curd', a description challenged by the footnoted observation that Shakespeare says 'Out vile jelly!' The likening of the smell of phosphine to that of garlic prompts the comment (p. 373) that this is 'A base libel on a plant recommended by the Father of Chemistry, HERMES, to ODYSSEUS, as an antidote to the poisons of CIRCE'.[14] A reference to 'saltpetre', potassium nitrate, is amplified by a note that the word means 'rock salt' and that this is itself a 'reminder that in bygone days chemists have found it very difficult to distinguish between substances of similar appearance' (p. 216). Elsewhere (p. 9), the reader is told that, in France, nitrogen is called azote (a name that indicates that the gas will not support combustion) and that the element cobalt is supposed to get its name from the German *Kobold*, a mischievous subterranean gnome that haunted the mines from which the ore was extracted (p. 508). All these references also appear in the 1952 publication, although the pagination is slightly different.

Holmyard's output as an author of school textbooks was not restricted to chemistry. *Science: An Introductory Book* was published in 1926, *General Science* appeared the following year and a three-volume series (*Physics/Chemistry/Biology for Beginners*) was published in 1930 (Holmyard 1930a, b, c). Intended for the first two years of secondary schooling, a reviewer of the series in *The School Science Review* welcomed it as 'three very excellent books', adding that it was 'a pleasure to meet school textbooks which are not pervaded by an atmosphere of public examination syllabuses' (SSR 1930, p. 190). In the 1930s, Holmyard also co-authored *Electricity and Magnetism for Beginners* (Badcock and Holmyard 1931); *Heat, Light and Sound for Beginners*; and *Mechanics for Beginners* (Barraclough and Holmyard 1931), published as part of a Modern Science Series. Badcock and Barraclough were two of Holmyard's colleagues at Clifton and he collaborated with a third Clifton colleague to write *Elementary Botany* (Graham and Holmyard 1935). He also edited J. A. Thomson's two-volume *Biology for Everyman* (Thomson and Holmyard 1934) and was one of the editors of an eight-volume *History of Technology*, published between 1954 and 1984 (Singer et al. 1954–84; see also Holmyard 1946).

Why were so many of Holmyard's historicised school chemistry textbooks such successful[15] publishing ventures? To some extent, his success stemmed from a

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[14] Holmyard believed strongly in the merits of a classical education, encouraging boys to study classics before taking up chemistry in the upper school, and he made frequent use of classical analogies, e.g. the 'passion of Hydrogen and Oxygen for one another causes as much trouble in the chemical world as that of Paris for Helen did in ancient Troy'.

[15] Although Holmyard's textbooks seem always to have been reviewed very favourably, reviewers were usually able to identify some matters that needed attention. Almost all of these related to a

clarity of style that allowed him to express complex ideas in ways that young pupils could readily access. One reviewer of his *Elementary Chemistry* described it as 'written in English which any boy can understand - the sort…which one seldom finds in a textbook' (SSR 1925b, p. 140). Recalling his schooldays at the Crypt School in Gloucester, Keith Francis, a school teacher who graduated in physics from Cambridge in 1956, described Holmyard as having a 'spicy' literary style that 'grabbed me' (Francis 2004, p. 15).[16] Holmyard's obituarist in *Nature* judged that 'many students' of the journal 'must owe their introduction to chemistry' to his inorganic and organic chemistry textbooks which presented the basic facts of chemistry 'as an experimental science, relating them to general principles in a way which gives them significance and interest' (Partington 1959, p. 1360).

In addition, although the illustrations in Holmyard's books were in black and white rather than colour, they were always carefully chosen, well related to the narrative and often appeared for the first time in texts intended for school use.

> The plates and pictures are delightful and make the book very attractive; after seeing page 73 all our boys will want to get out and collect marsh gas –which is as it should be! (*idem.*)

> The illustrations are admirable and almost all unfamiliar. (SSR 1933, p. 126)

His textbooks also had a readily discernible structure that enabled information to be easily located and, if necessary, retrieved for homework or revision purposes. This became increasingly important as the numbers of candidates attending grant-aided secondary schools and entered for public examinations both increased in the interwar years. The number of pupils attending grant-aided secondary schools increased from 269,887 in 1919 to 470,003 by 1938, although by no means all of these completed their secondary schooling.[17] Aided by grants from the Board of Education, the number of 'advanced', i.e. sixth form, courses in science also increased. By 1938, physics and chemistry each accounted for just under one third of all entries for the Higher School Certificate Examination taken at the end of secondary schooling; the biological sciences (botany, zoology and biology) had yet to establish a secure place in the curriculum of many secondary schools, especially those for boys (Jenkins 1979).

The long publishing history of many of Holmyard's textbooks was also facilitated by the fact that school examination syllabuses in chemistry and physics in England

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few typographical/proof reading errors or other relatively minor defects. One notable exception was a reviewer of Holmyard's *A Junior Chemistry* (Holmyard 1933). While writing that the book would be 'read with delight by any boy or girl without any need for external stimulus', the reviewer wondered whether 'a boy of 14…may be aggravated by the use of an appeal in the second person singular and of exclamation marks' (SSR 1933, p. 126).

[16] Francis also describes Philbrick and Holmyard's *Theoretical and Inorganic Chemistry* as a 'treasure' and recalls how, as a 13-year-old pupil, it enabled him to know everything that Tarzan [the nickname of his chemistry teacher!] wanted to teach him (Francis 2004, p. 15).

[17] These figures need to be set alongside the much larger number of pupils who attended public elementary schools in England and Wales: 5,933,458 in 1920–1921 and 5,087, 485 in 1937–1938. The division between elementary and secondary education reflected significant differences in social class. It was only after the Education Act of 1944 that all pupils passed from a primary to some form of secondary schooling (grammar, secondary modern or technical).

underwent astonishingly little change between 1918 and the curriculum reform movement of the 1960s. Save for the replacement of Imperial units by the centimetre-gramme-second (cgs) system, examination questions in physics set in the 1920s first appeared in much the same form over a generation later. In chemistry, candidates continued to be examined on their detailed knowledge of the manufacture, preparation and properties of the elements and their compounds with questions following a standard format year after year (Jenkins 1979, p. 293). In Bassey's judgement, Ordinary-level chemistry texts had followed 'one familiar and well-worn path' which, by 1960, had become 'a rut rather than a highway' (Bassey 1960, p. 14).[18] There is little doubt that this judgement can be applied, although to a lesser extent, to school texts in physics and biology and those intended for more senior secondary school students.

Holmyard was also able to call upon his experience both as a teacher and as an examiner for the former Northern Universities Joint Matriculation Board (NUJMB). Indeed, the preface to his *A Higher School Certificate Inorganic Chemistry* informs the reader that 'the allotment of space to individual topics is roughly in proportion to the frequency with which these topics appear in the examination papers', although he is very careful to make clear that more is needed in any textbook that 'aspires to do something more than cram', an aspiration that one reviewer readily acknowledged.

> The author is no Polyphemus and his other eye has watched the cultural aspect of chemistry to prevent the work from degenerating into a mere cram book. (*J. Chem. Ind.* 1940, p. 50)

Holmyard's footnotes and historical commentaries were an integral part of this 'something more', and it would be a serious error to dismiss them as idiosyncrasies or regard them as mere ornaments intended to display the author's undoubted erudition. Footnotes and comments they may be, but they formed part of a coherent and distinctive volume that enlivened, enriched and contextualised school chemistry and its nomenclature, then far from standardised, in ways that have not been matched. No one reading Holmyard's texts can avoid learning something of the many roles that chemistry has played and continues to play in recorded history. Reading them today indicates just how much has been lost from chemical education.

74.5 Historical Approaches: The Wider Context

Holmyard was by no means the first to argue for a historical approach to the teaching of school science nor was he alone among his contemporaries in writing historicized chemistry textbooks (e.g. Partington, Cochrane, Lowry).[19] As long ago as 1855, the

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[18] Bassey used Holmyard's *Elementary Chemistry* as 'the standard treatment' with which to compare other school chemistry texts in print at the time of his survey.

[19] J. A. Cochrane's *Readable School Physics* (1923) and his *School History of Science* (1925) were highly successful publications, both of which have recently been made available once again. The former was part of a Natural Science Series published by Bell and edited by Holmyard. J. R. Partington, professor of chemistry at the University of London, had studied with Nernst and

president of the British Association for the Advancement of Science, the Duke of Argyll, told his audience in Glasgow that what was wanted in the 'teaching of the young, is not so much the mere results, as the *methods* and, above all, the *history of science'* (BAAS 1856, p. *lxxxiii*). Nor was Holmyard to be the last: over a century and a half later, the history of science featured in a national curriculum introduced for the first time in England (DES 1989). Even more recently, the European Commission has argued that 'a renewed pedagogy' which presents 'the processes and methods of science together with its products' is essential for the 'Future of Europe' (EC 2007, p. 16).

Among Holmyard's contemporaries, Edgar Fahs Smith (1854–1928) in the USA, chemist and author of biographies of several American chemists (Smith 1914), was said to be 'fond of theories in an historical way, but used the luxury of their downfall by experimental observation to illustrate the fallacy of theories'. This quotation is cited in Fowles who attributes to Smith the expression 'Facts remain, theories may change overnight'(Fowles *op.cit.,* pp. 516–7). Among Fahs's successors in the USA, Conant's *Case Histories* (Conant et al. 1957; see also Conant 1947), the *Harvard Project Physics*(1970), the *National Science Education Standards* (NRC 1996), *Benchmarks for Science Literacy* (AAAS 1993), the textbooks of Taylor (1941/1959) and Rogers (1961) and initiatives such as McComas's use of historical examples to illustrate key aspects of the nature of science (McComas 2008) all testify to the enduring appeal of the history of science as a pedagogical tool. Given the profound changes that have taken place in science, philosophy, psychology and society since science was first schooled in the mid-nineteenth century, this widespread and enduring desire to call upon the history of science to illustrate something of the 'nature of science' calls for some comment.

Holmyard's historical approach to teaching science should not be equated with simply incorporating biographical or other elements of the history of science within school science curricula, an accommodation with which many science teachers would have felt much more comfortable and which seems to have met with more success. However, an inadequate knowledge of the history of science and its attendant risk of an unhelpfully Whiggish approach to history were problems common to

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was the author of advanced chemistry textbooks, of *A Short History of Chemistry* (1937) and of a four-volume history of chemistry Partington (1961–4). His elementary text, *Everyday Chemistry*, is divided into three parts of which the first is entitled 'Historical and Theory' (Partington 1929). A reviewer of Partington's *A College Course of Inorganic Chemistry* (1939) warned his readers that 'Professor Partington has written so many books that have been distinguished by their lucidity and accuracy that a reviewer reading a new book by him begins by being prejudiced in his favour' (*J. Chem. Ind.* (1939) 58 (44), p. 974). A similar comment might well have been made of Holmyard. In 1965, the year of his death, Partington was awarded the George Sarton medal. Thomas Martin Lowry, FRS, worked with H.E. Armstrong from 1896 to 1913 and later became professor of physical chemistry at Cambridge. With J.M. Brønsted, Lowry introduced a new and broader definition of acids and bases. Lowry's generously illustrated *Historical Introduction to Chemistry*, first published in 1915, presents 'a historical account of the more important facts and theories of chemistry, as these disclosed themselves to the original workers' (Lowry 1915, preface). Although perhaps more appropriate for teachers than school students, the book is a further indication of the steady stream of educators who have regarded the history of science as an important component of science education.

both. In addition, as Brush was to suggest later (Brush 1974), introducing students to the history of science might not accord with a desired canonical account of scientific discovery. Even so, whether as a pedagogical approach or as a component of a school science curriculum, the history of science is a striking feature of the history of school science education. Why is this?

Part of the answer may lie in the fact that renewed calls to attend to the history of science have often coincided with a perception that the school science curriculum is in difficulty or facing challenges that prompt a need for reform. As noted above, the desire in the interwar years to 'humanise'[20] school science by teaching the history of science owed much to the feeling that in making possible the unparalleled slaughter of the First World War, science – and chemistry in particular – had lost a sense of moral purpose that it urgently needed to regain. The emphasis on science in Germany came to be seen as having led not only to economic prosperity but also to the moral collapse responsible for the war in which the Allies had been engaged. Restoring that sense of purpose seemed to require reform of the school science curriculum and the history of science pointed a way forward.

> …the teaching of science must be vivified by a development of its human interest, side by side with its material and mechanical aspects… [and] it must never be divorced from those literary and historical studies that touch most naturally the heart and the hopes of mankind. (Natural Science in Education 1918, para. 3)

The contrast with the aftermath of the Second World War is striking.[21] Despite the advent of nuclear war, science and technology emerged from that war with their prestige greatly enhanced. The consequent demand for reform of school science education was governed by the urgent need to increase greatly the supply of qualified scientific and technological personnel, both for civilian and, at the height of the Cold War, military purposes (Rudolph 2002). The history of science was seen as, at best, only marginally relevant to achieving this goal. Supported by a psychology that favoured 'learning by discovery', the emphasis in what became a global movement for science curriculum reform was captured by Bruner's claim that 'a schoolboy learning physics *is* a physicist' (Bruner 1960, p. 14), a claim repeated by Harlen with respect to primary education in the UK almost forty years later: '*Learning science*

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[20] For a historical perspective on the humanist critique of the place of science in the school curriculum, see Donnelly (2002), Donnelly (2004) and Donnelly and Ryder (2011). See also Mayer (2005). For a discussion of science as humanism in Denmark in the 1950s, see Lynning (2007). It is worth noting that there have been frequent calls to 'humanise' other abstract disciplines, e.g. economics (Solterer 1972) and mathematics (Guting 2006). Indeed the word 'humanising' has perhaps acquired something of an Alice in Wonderland quality, writers taking it to mean what they wish it to mean. In 1924, the author of an article in *The North American Review* asked 'By the plain light of noon, what is implied in "humanizing" science?' (Glaser 1924, p. 230). Today, as searching the Web reveals, the science education literature is replete with references to humanising school science education, offering a variety of rationales and strategies for bringing it about. See, for example, Watts and Bentley (1994), Kipnis (1998), and Clough (2009).

[21] However, at least one prominent science educator felt much the same about the role that science was also playing in the Second World War. See Westaway's *Science in the Dock: Guilty of Not Guilty?* (1942).

and *doing science* proceed in the same way' (Harlen 1996, p. 5). In the USA, students following *ChemStudy* courses were promised that they would 'see the nature of science' by engaging in scientific activity' and thereby to 'some extent' become scientists themselves (Pimentel 1963, p.1 and preface). In the UK, despite an assertion[22] by the Science Masters' Association and the Association of Women Science Teachers that science was an 'active humanity' (SMA 1961, p. 5), canonical science was to be presented in a way that enabled students to 'think in the way practising scientists do' (Halliwell 1966, p. 242). Much that followed, such as *Process Science* and *Science in Process,* also sought to introduce students to the nature of science by involving them in suitable practical, laboratory-based exercises designed to encourage the acquisition of those allegedly discrete skills and processes (communicating, interpreting, observing, planning investigations etc.) that in sum enabled them to be good at science (Coles 1989, pp. 4–5).

During the 1960s, it gradually became clear, both in the UK and the USA, that the large-scale efforts to reform school science education had not succeeded in increasing, or in some cases even stemming, the numbers of young people wishing to study the physical sciences, especially physics, beyond compulsory schooling. In England, the Council for Scientific Policy set up a committee, chaired by the eminent chemist Frederick Dainton,[23] to 'examine the flow of candidates in science and technology into higher education' (Council for Scientific Policy 1968). Although the committee's conclusion that there was a 'swing from science' in schools was soon challenged (e.g. McPhemon 1969), it received widespread publicity (e.g. AAAS 1968) and prompted a wide range of research studies of possible causes of the 'swing' away from what have become known as the STEM subjects. Such causes remain the focus of ongoing investigation in many countries (Sneider 2011). In the USA, it was clear as early as 1963 that the PSSC course had attracted 'only about 4 % of the two and a half million senior students in high school, and the total fraction taking *any* physics course was under 20 %, and relatively shrinking' (Holton 2001, p. 2).Once again, the history of science was seen as one way of easing, if not overcoming, the problem. Holton, in a review of the *Harvard Project Physics* course, has recalled how he and others were invited to a meeting by the National Science Foundation at which they were asked

> who would come to the aid of the country? For in those days it was thought without more science-literate students the Russians might get us. (*idem.*)

Holton's answer eventually led him to become the principal investigator of *Harvard Project Physics* and thereby to develop a 'humanistic, historically oriented course for schools' that presented physics, as in his original text (Holton 1952), 'not

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[22] For the Science Masters' Association, if more emphasis were placed upon the cultural and humanistic sides of science education, this might not only lead more young people to study science but encourage them to favour science teaching as a career (SMA 1957).

[23] Dainton, speaking in 1971, used the memorable phrase 'voluntarily withdrawn from human contact; disassociating himself from personal and societal problems… a man who is "objective" to an objectionable degree', to describe how scientists were widely perceived at the time (Dainton 1971, p. 18).

just as one damned thing after another, but a coherent story of the result of the thoughts and work of living beings' (Holton 2001, p. 2). The outcome was the sort of course that Holmyard would have welcomed, especially the illustrations taken from seminal documents in the history of science that appeared in the course book. Interestingly, the initial reaction of the National Science Foundation to the fact that course wasn't going to be pure physics was one of 'horror'! By the time the final edition of the book was published in 1970, there was significant evidence that it was having an impact on the numbers of students studying physics at high school and college. As many as 300,000 students per year were studying some or all of the course materials and the percentage taking physics, particularly among women students, had increased markedly, 'with some 20 % of all high school students taking *Project Physics,* and in use also in some colleges' (Holton 2001, p. 4).

Although further growth of *Project Physics* in schools (the reference to Harvard in the title was abandoned amid concerns over 'elitism!') fell foul of the phasing out of sections of federal support for science education in the 1970s, especially funds for science teacher education, it acquired a new lease of life when the USA once again sought to reform school science education, this time by prioritising the need for a scientifically literate citizenry, although a number of other factors were involved, e.g. the demand from teachers for a revised and updated version of the project materials and the need to improve the understanding of physics on the part of a new generation of physics teachers. As noted above, the AAAS *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996) both attached importance to the history of science. The former included an entire chapter devoted to 'Historical perspectives' (chapter 10), while the latter advised standards for the history of science from K4–12. The revised edition of the earlier text, published in 2002 under the title *Understanding Physics* (Cassidy et al. 2002), was described by Holton as the 'completion of a great circle, spanning four decades, from the first draft in 1962…through the slough of the early 1980s and now on to the rising of the new Phoenix' (Holton 2001, p. 6).

That circle offers an interesting example of how a federally funded history of science initiative in the USA, initially prompted by manpower and defence concerns, came to be recast and called in aid of the perceived national need to promote science for all and enhance the general level of scientific literacy. There are some parallels here with the UK, not least in the political anxiety about scientific literacy and the levels of public understanding of science, although the picture is complicated by profound differences in the education systems of the two countries and, more particularly, by the development of a non-selective system of secondary schooling and the subsequent introduction of a statutory national curriculum in England and Wales in 1989. By requiring all students to study science from the age of 5 to 16, it was hoped that this would in due course both promote scientific literacy and develop a larger cohort of students choosing to study science, especially physical science, beyond compulsory schooling. The UK government clearly saw compulsion as a more effective policy initiative than the large-scale curriculum reform of a generation earlier. Despite this, the initial version of the national curriculum included a component (known as an attainment target) that drew upon contemporary views from both the history and the sociology of science. Its inclusion prompted the editor of the *British Journal for the History of Science* to offer the following somewhat slightly anxious comment.

> The overriding statement of intent…is one that might be welcomed by the most radical exponent of the view that scientific knowledge is shaped by social, economic and political context. (BJHS 1990, pp. 1–2)

In the event, the first version of the national curriculum almost immediately proved unworkable and very little of the history of science survived into the revised statutory science curriculum introduced in 1991,or indeed into the several revisions that have taken place since (Donnelly et al. 1996;Donnelly and Jenkins 2001). It has largely been left to individuals and non-governmental sources to take initiatives to promote the history of science in science education.[24]

Advocacy of the history of science in aid of science curriculum reform may also owe much to historians of science themselves. Holmyard and Holton stand as two obvious examples, from different generations and countries, of scholars in the history of science giving attention to the form and content of school science curricula. Their pedagogical interest, however, is part of a much longer-standing and wider interest among their fellow professionals that has been well described by Brock (1989) and Sherratt (1980). There has been an equally long-standing interest on the part of many school science teachers in the history of science and in the contribution that it might make to their teaching. Practising and former science teachers were among the founding membership of the British Society for the History of Science in 1946 and their professional association, The Science Masters' Association and its successor from 1963 onwards, the Association for Science Education, collaborated with the BSHS in a variety of curriculum and policy initiatives (Brock 1989, p. 33 *et seq.*). In addition, history of science books was regularly reviewed in *The School Science Review* and the titles included in the suggested list of *Science Books for a School Library* issued from time to time as a supplement to the association's journal.

The motives of both organisations and their members in promoting collaboration are, as always, historically contingent. Closer involvement with the work of the schools has had the advantage of bringing the history of science to the attention of teachers and students who, in turn, were able to take advantage of historical expertise to their mutual benefit. This no doubt was an important consideration, especially in its early years, for the Department of the History and Methods of Science at University College London which directed its efforts 'chiefly at science teachers and thus at secondary education' (Mayer 1999, p. 233). On some occasions, notably in the interwar years, the rhetoric underpinning this mutual interest related strongly to humanising science teaching and to reasserting the cultural value of science. At other times, the language has been that of bridging the 'two cultures' identified by Snow in his 1959 Rede lectures (Snow 1959, 1964), although the

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[24] For example, the *Perspectives on Science* course developed at Rugby School in Warwickshire (www1.edexcel.org.uk/Project/POS-Briefing.doc) and the Public Understanding of Science course developed at the University of York (http://www.nuffieldfoundation.org/science-public-understanding), both accessed 30 January 2012.

emphasis upon science as a ‘humanity’ has never been lost (Council for Scientific Policy *op. cit.,* para. 181). Most recently, the history of science has been cast as an element of the ‘nature of science’ which has come to figure so prominently in science curricula across the world, while pedagogy (McComas 1998) and the form and practice of scientific research have become fields of scholarly academic interest to historians of science (Kaiser 2005). That is perhaps another ‘great circle’ that is in the process of being completed.

74.6 Conclusion

How might Holmyard’s work be viewed in the light of the changes outlined above? Among his alchemical studies, his work on Geber[25] was of seminal importance, and like all sound scholarship, his research as a historian of science has provided a platform upon which other scholars have been able to build. J. R. Partington, himself a distinguished historian of chemistry and textbook author, judged that Holmyard’s alchemical studies were of ‘permanent value’. Noting that alchemists and early chemists believed that metals were composed of mercury and sulphur, Partington drew particular attention to Holmyard’s finding that this theory, promoted by Geber, derived from a statement in Aristotle’s ‘Meteorology’ (Partington 1959). Holmyard’s 1957 book, *Alchemy,* was published in several languages, reprinted in 1990 and remains an important and readable survey of the subject. His obituarist in *Ambix* offers a useful overview of Holmyard’s alchemical studies and comments that he added to ‘our knowledge of this subject…its great names, its theories, its experiments and its apparatus’. His conclusion is that Holmyard brought about ‘a greater interest in and an improved understanding and appreciation of the work and writings… of …Muslim chemists in general’ (McKie 1960, p. 5).

Although Holmyard’s school chemistry textbooks were written for syllabuses and examinations that differ greatly from those confronting students in the early years of the twenty-first century, they remain an important model for any author wishing to present chemistry, not simply as a discipline, but as an integral part of a wider cultural history. Reading some of his textbooks helps the reader understand that interest in the behaviour of materials and the desire to understand how they may be changed from one to another is at least as old as recorded history. At the end of a chapter entitled ‘How Chemistry Arose’, Holmyard invites the reader of his *Elementary Chemistry* to answer questions such as the following:

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[25] Geber is the Latin equivalent of Jâbir, and the name was used by the author of an influential series of alchemical texts in the fourteenth and fifteenth centuries. It seems likely that this Latinised version of the name was adopted by a Western writer in order to heighten the authority of his own work: Holmyard’s ‘likely guess’ (Holmyard 1957, p. 134) was that these later mediaeval works were written by a European scholar, possibly in Moorish Spain. Holmyard was able to identify the eighth-century alchemist Jâbir Ibn Hayyân who held a court appointment under the Caliph Harun al-Rashid. A lengthy examination of the ‘Geber problem’ is available at www.history-science-technology.com.

> Mention some of the chemical facts and processes known to the Ancient Egyptians.
>
> Explain how it was that the Muslims were able to establish chemistry on a sound basis.
>
> Who was Paracelsus? What service did he render to chemistry?

Anyone who follows the historical journey that Holmyard sets out so skilfully in his texts will therefore travel with him to China, India and Arabia as well as within Europe, glimpsing other languages and cultures on the way and learning that it is all too humanly possible to take a wrong turning while firmly believing it is the way forward. The journey that he offered was much less familiar in the first few decades of the twentieth century than is the case today when societies have become much more multicultural and scholars more aware of non-Western contributions to the development of science.

Although Holmyard's evolutionary approach found limited favour, his advocacy did much to draw attention to the contribution that the history of science could make to school science education and to encourage teachers to incorporate historical components within their teaching. In doing so, the various attempts to 'humanise' school science teaching presented challenges and problems that have a contemporary international relevance as attempts are made to accommodate the history of science within the movement to promote the teaching of the 'nature of science'. As experience with *Harvard Project Physics* confirmed, addressing and overcoming these challenges and problems requires a substantial investment in science teachers' professional development that is grounded in collaboration between those whose scholarly expertise lies in the history of science and those teaching science in schools. That can succeed only if there is agreement about the contribution that the history of science can legitimately make to the science curriculum and if science teachers enable their students to think historically as well as scientifically. Fortunately, the form and content of that contribution are now matters not only for lively but well-informed debate but also for science curriculum development (e.g. Holton 2003; Matthews 1994/2014, 2009; Kokkotas et al. 2009).

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Chapter 75
John Dewey and Science Education

James Scott Johnston

75.1 Introduction

John Dewey is perhaps the most well-known philosopher of education of the twentieth century. His output was prodigious and he is distinctive for placing education at the centre of important philosophical discussions. Dewey has in addition a series of attentive accounts on traditionally philosophical topics, such as theory of knowledge, meaning, experience, reality, ethics, political and social theory and aesthetics—all of which count education as important. Dewey's most important educational treatises include *The School and Society* (1899), *How We Think* (1910), *Democracy and Education* (1916) and *Experience and Education* (1938), and the former three were in use as textbooks for hundreds of thousands of teachers in teacher-training programmes in America over several decades in the first half of the twentieth century. Dewey continues to have an influence on teacher training and, important for our purposes here, science education.

In this chapter, I will concentrate on three themes: Dewey's theory of experience and the role of reflection or thought, Dewey's theory of inquiry (scientific method) and Dewey's claims for science education. The three are interrelated and discussing Dewey's claims for science education presupposes discussing his theories of experience, reflection and inquiry. I will follow with a brief discussion of recent developments in science education that have invoked and used Dewey: constructivism and science education, science education and models of inquiry in the curriculum, and the teaching of science. I will finish the chapter with my assessment of the scholarship on Dewey and science education.

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75.2 Brief Biographical Sketch

John Dewey was born in Burlington, Vermont, on April 22, 1859. He grew up in Burlington and attended the University of Vermont. Dewey taught high school for 2 years in Oil City, Pennsylvania, and a further half-year in Charlotte, Vermont, prior to attending graduate study in philosophy at newly minted Johns Hopkins University under advisor, George Sylvester Morris. Having graduated in 1884, Dewey began his university career at the University of Michigan (1884–1888; 1890–1893) and the University of Minnesota (1888–1889), followed by the University of Chicago (1894–1903) (where he ran the famed laboratory school) and, finally, Columbia University in New York (1904–1927) where, in addition to an appointment as professor of philosophy, he was also professor of pedagogy at Teachers College. Dewey married Alice Chipman in 1886, and together, they raised seven children, though two died at very young ages. Dewey would also adopt two children. Dewey travelled and lectured extensively, especially in later life, most famously in Russia, China, Turkey and Mexico. After retirement from active teaching in 1930, his already prodigious output increased; when he died in 1952 in New York City at the age of 92, he had published some 47 books and 1,500 articles.

75.3 Dewey's Philosophical Project

Dewey's philosophical project was to aid in the bringing of the attitudes, criticisms, methods and results of philosophers to bear on practical concerns (Middle Works (MW) 10, 47). As well, it was to make philosophy and philosophers a valued enterprise for the task of democratically associated living (MW 9, 91). Dewey famously claimed that philosophy was the 'criticism of criticisms' and that this ought to be put to work in social and cultural transformation (Later Works (LW) 1, 309). Central to his philosophical project was the 'method of intelligence' (MW 10, 45), variously understood as 'inquiry', 'problem-solving', 'how we think' and 'scientific method'. Though Dewey sometimes distinguished between these (largely on the basis of context), they were coterminous in the project of getting philosophy (and other disciplines) to bear on what Dewey considered 'the problems of men' (MW 10, 48).

75.4 Dewey's Educational Project

Formal education has many important aims and functions, but in terms of science and science education, this one stands out: education was for Dewey the chief means with which to inculcate in the species the problem-solving method of intelligence needed to overcome extant social problems. Having said this, other aims and functions of education are coterminous with the development of the method of intelligence. Social and cultural transmission of past matters of fact and the techniques to solve what Dewey refers to as ‘problematic situations’ (LW 12, 112) is one example. Growth, which is the natural end of individuals and the human species (and is sometimes said by Dewey to be *the* end of education (e.g. MW 9, 47–49; LW 13, 19)), is another. To utilize the method of intelligence is to draw on past matters of fact and techniques, and to grow is to transform oneself and one’s environment in accordance with a set of problem-solving methods, as I will discuss further in the section on inquiry.

75.5 Deweyan Inquiry

Dewey discusses inquiry variously, and in several key texts and articles. What I will do here is provide a summary exegesis of his various claims, beginning with the relation between experience and inquiry, followed by a discussion of Dewey’s claims for the stages of thought, the role of specifically scientific thinking in inquiry and the role of scientific inquiry in the social sciences.

75.5.1 The Foundation of Inquiry: Experience

Dewey rejects the empiricist notion that we assemble bits of information through our sense-perceptive faculties and reorder them as ideas in the mind. He also rejects the rationalist notion that ideas are innate or otherwise necessary and pure principles that bear down on our sense-perceptive apparatus to fashion objects of the mind. What Dewey offers is an account of experience in which we exist in a world of what he would call ‘brute facts’ and ‘thats’ (MW 3, 164), a world that is first felt rather than cognized (LW 5, 249). What we experience as felt is a whole, not an object. Nor is a felt whole a mere feeling. It is rather that the felt whole is what we experience—as an immediate quality. The human organism exists in a qualitative state, and when she experiences, she does so qualitatively, through feeling. Feeling, in turn, is dependent on generic ‘traits of existence’, which arise out of every encounter of the human organism with the world (LW 1, 308). These traits are ‘qualitative individuality and constant relations, contingency and need, movement and arrest…’ (LW 1, 308). Dewey adds to this list ‘rhythm and regularity’ and ‘our constant sense of things as belonging or not belonging, of relevancy…’ (LW 10, 198). Not every experience will have these traits as rich and defined as others. Most experiences are ‘mundane’; they evince some traits of existence but not of sufficient quality to be notable. Those experiences that do, Dewey considers to be consummatory. A consummatory experience is one in which the experience is felt and taken as a qualitative whole, a unity and a totality.

Inquiry begins and ends in experience. Experience in turn supplies inquiry with the situations or events from which inquiry forms what Dewey calls ‘thought’ or ‘reflection’. In the attempt to reproduce the event or situation that led to the consummatory experience, the human organism will be poised to attempt reflection. Dewey in one place calls this a ‘judgment of appreciation’ (LW 12, 177–178). Successful reflection will eventually lead to the isolation of the factors involved in the event, together with their control and prediction for further events. However, Dewey cautions we must not confuse the resultant appreciation which is felt, with the operations that bring the material into harmony. To do so is to hypostatize feeling into generalizations (LW 12, 179). Such, historically, is the case with the good, the true, the beautiful and other ‘absolutes’.

Dewey discusses the way in which we are induced to reflect upon our experiences. This occurs when we have and undergo an unsatisfying experience when we expect a satisfying or otherwise unproblematic one; an experience that has a paucity or (as Dewey sometimes says) imbalance of the traits of existence and that does not lead to a qualitative whole. In the context of inquiry, Dewey calls the event or situation that concludes in an unsatisfying experience a ‘felt difficulty’ or ‘indeterminate situation’ (MW 6, 237; LW 12, 108). We then undertake inquiry to ‘determine’ the situation. When we are able to order and control the qualities or traits of the experience of an indeterminate situation, we form an experience that is complete, satisfying and qualitatively whole. Indeed, this is the basis of Dewey’s most famous definition of inquiry: ‘Inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole’ (LW 12, 108).

75.5.2 The Rise of Science and Scientific Thinking

The self-awareness of the role of reflection and its various techniques and stages obviously did not arise at once: it was the result of thousands of years of investigation (much of it haphazard or misleading) into the forces of nature, the constitution of material objects of use (technologies) and the increasing role of methods in ascertaining instrumental results. For much of this history, the establishment of methods and principles of science fell to philosophy, and Dewey characteristically concentrates his examination of the history of the rise of science and scientific thinking to developments within philosophy. Dewey’s thesis is that a previously stable set of affairs (both individually and species wide) is upset, unsettled or otherwise rendered dubious. The tension leading to instability is the impetus for further questioning, investigation and inquiry, and this leads (if successful) to a readjustment, a resettlement. We understand this through recourse to a historical/developmental and evolutionary account of the rise of science—what Dewey calls ‘the genetic method’ (MW 1, 150; MW 2, 300–301). We have here the pattern Dewey would use in his discussion of inquiry generally—a pattern made famous in his discussion of the stages of thought in the two editions of *How We Think* (1910: 1932) and in his definition of inquiry as the settlement of an unsettled or indeterminate situation in *Logic*: *the Theory of Inquiry* (1938a).

Dewey's concentrated attention on the rise of scientific thinking through history is best exemplified in the early, extended essay, 'Some Stages in Logical Thought' (1903) together with his book, *Reconstruction in Philosophy* (1920). In his essay, Dewey notes four stages in the development of logical thinking: the magical thinking of the earliest societies, the dawning awareness of the need for method in ancient civilizations, the isolation and abstraction of principles and standards in ancient Greek (Hellenistic) societies and, finally, the rise of a scientific method in the seventeenth century and beyond (MW 1, 172–173). In *Reconstruction in Philosophy*, Dewey alters his stage account of the rise of scientific thinking, noting specifically religious, metaphysical and scientific eras. In the religious era, Dewey claims, 'Savage man recalled yesterday's struggle with an animal not in order to study in a scientific way the qualities of an animal or for the sake of calculating how better to fight to-morrow, but to escape from the tedium of to-day by regaining the thrill of yesterday' (MW 12, 80). In the metaphysical era, 'The growth of positive knowledge and of the critical, inquiring spirit undermined those in their old form…' (MW 12, 89). What was left, according to Dewey, was to 'Develop a method of rational investigation and proof which should place the essential elements of traditional belief upon an unshakeable basis; develop a method of thought and knowledge which while purifying tradition should preserve its moral and social values unimpaired' (MW 12, 89–90). Finally, in the scientific era proper, the recognition of the genetic method—a method at once empirical, experiential, and scientific, historical and developmental—is the best assurance of producing practically valuable investigative results (MW 12, 93).

75.5.3 The Stages of Thought

In *How We Think* Dewey outlined and then expanded upon the stages of thought. Thought for Dewey is synonymous with reflection and inquiry: to think is to pass through the stages or phases of inquiry, from a problematic situation first felt, to the articulation of a problem, to the imagination of various anticipated outcomes, to the actual testing of the results using the various techniques and operations of isolation, ordering and control and prediction of phenomena, and finally, to the objective settlement and felt resolution or satisfaction of the original problematic situation. Thinking or inquiry is in other words, loosely circular. Here, I will spell out the various stages of thought. Dewey first gives a summary estimation of the five stages of the '…complete act of thought' (MW 6, 236). 'Upon examination, each instance [of genuine thought] reveals, more or less clearly, five logically distinct steps: (i) a felt difficulty; (ii) its location and definition; (iii) suggestion of positive solution; (iv) development by reasoning of the bearings of the suggestion; (v) further observation and experiment leading to its acceptance or rejection; that is, the conclusion of belief or disbelief' (MW 6, 236–237).

All genuine thought begins with a problematic situation, which for Dewey manifests as 'a felt difficulty' (MW 6, 237). This is the experiential basis of all thinking: a genuine inquiry can only take place if a genuine problem is found and established. Genuine problems are those that are felt, rather than abstracted or given ready-made to students, and Dewey hammers this point home in all of his educational writings. Felt difficulty may take various shapes. It may exist as 'emotional disturbance, as a more or less vague feeling of the unexpected, of something queer, strange, funny, or disconcerting' (MW 6, 238). Again however, what is important is that 'observations deliberately calculated to bring to light just what is the trouble, or to make clear the specific character of the problem' are undertaken (MW 6, 238).

In the second stage of thought, a clearly articulated problem is set forth. It is imperative that the problem be set forth consciously, because the techniques and operations of further stages of inquiry cannot be properly marshalled unless 'the trouble--the nature of the problem—has been thoroughly explored' (MW 6, 238). Failure to fully articulate the problem prior to engaging in experimentation with ideas and techniques of order and control of variables leads to frustration and dead ends—a sort of 'mission creep' that very often nets results for no particular problem, leading to failure for inquiry. As Dewey puts it, 'The essence of critical thinking is suspended judgment; and the essence of this suspense is inquiry to determine the nature of the problem *before* proceeding to attempts at its solution. This, more than any other thing, transforms mere inference into tested inference, suggested conclusions into proof' (MW 6, 238–239, emphasis mine).

The third stage Dewey calls 'suggestion'. Suggestion is that idea in which 'the perplexity…calls up something not present to the senses....Suggestion is at the very heart of inference; it involves going from what is present to something absent. Hence, it is more or less speculative, adventurous…The suggested perception so far as it is not accepted but only tentatively entertained constitutes an idea' (MW 6, 239). In this stage, what Dewey elsewhere calls a 'dramatic rehearsal', wherein we reconstruct the situation in thought and attempt to control for the various conditions, takes place (LW 10, 81–82). We are literally putting forth scenarios of possible outcomes, through varying the conditions of experimentation in thought. Here, tentative hypotheses are formed, thought through and passed or rejected according to the results of the thought experiment.

In the fourth stage of thought, more extensive inferential operation is carried out on those hypotheses that bear fruit in the earlier stage. In the earlier stage, we produce ideas—anticipated consequences of possible measures of control. 'As an idea is inferred from given fact [isolated from the situation], so reasoning sets out from an idea…' (MW 6, 239). Dewey continues

> …intimate and extensive observation has [its way] upon the original problem. Acceptance of the suggestion in its first form is prevented by looking into it more thoroughly. Conjectures that seem plausible at first sight are often found unfit or even absurd when their full consequences are traced out. Even when reasoning out the bearings of a supposition does not lead to rejection, it develops the idea into a form in which it is more apposite to the problem…The development of an idea through reasoning helps at least to supply the intervening or intermediate terms that link together into a consistent whole apparently discrepant extremes. (MW 6, 240)

Finally, the fifth stage or the conclusion of the 'complete act of thought' is 'some kind of *experimental corroboration*, or verification, of the conjectural idea…If we look and find present all the conditions demanded by the theory, and if we find the characteristic traits called for by rival alternatives to be lacking, the tendency to believe, to accept, is almost irresistible' (MW 6, 240). This is the conclusion to the problematic situation that initially led to the complete act of thought. That is, it is the *existential and qualitative termination* of the original problematic situation. Such terminations are existentially satisfying; they are the terminations of complete experiences—the sort that lead us to further investigation of the traits of existence of which they are constituted.

Dewey's stages of thought have sometimes been taken to be fixed steps that all thinkers must ascend in linear fashion. This is a mistaken interpretation of Dewey's complete act of thought. Dewey's stages are recursive: whenever one of the steps is engaged, the entire procedure is engaged. The recursive nature of the stages allow for the possibility that a complete act of thought occur even if the stages are not engaged in a linear manner. This allows for inquirers to enter the procedure without beginning at the first stage. Likewise, inquirers may exit the procedure prior to closure.

75.5.4 The Logic of Inquiry and Scientific Thinking

As discussed with reference to Dewey's *How We Think*, inquiry begins with a 'felt difficulty' (MW 6, 237); in *Logic: the Theory of Inquiry*, Dewey calls this an 'indeterminate situation' (LW 12, 108). It is an existential *and* felt difficulty that initiates an inquiry. However, a doubt does not carry us far: 'Organic interaction becomes inquiry when existential consequences are anticipated; when environing conditions are examined with reference to their potentialities; and when responsive activities are selected and ordered with reference to actualization of some of the potentialities, rather than others, in a "final existential situation," is inquiry properly speaking, begun' (LW 12, 111). A felt difficulty and indeterminate situation must be followed by a judgment for inquiry proper to be undertaken, a judgment that this situation is problematic (LW 12, 111–112).

Once a problem has been identified and a judgment rendered, the investigator searches out 'the constituents of a given situation which, as constituents, are settled' (LW 12, 112). We begin with these because they are settled (Dewey uses the example of the location of aisles and exists in a hypothetical fire at an assembly hall). The first step in the determination of a problem is to assemble these settled constituents in observation. Dewey says 'A possible relevant solution is then suggested by the determination of actual conditions which are secured by observation' (LW 12, 113). This solution, in turn, becomes an idea: anticipated consequence that is then carried out in practice (LW 12, 113). Observed facts are existential, in that they directly bear on the phenomena to be examined and/or tested; 'ideational subject matters' are of conceptual import. They concern other ideas and, specifically, the way these relate to one another (LW 12, 115). 'Ideas are operational in that they instigate and direct further operations of observation; they are proposals and plans for acting upon existing conditions to bring new facts to light and to organize all the selected facts into a coherent whole' (LW 12, 116). Existential facts and ideational subject matters are to be operationalized—tested out in an existential situation. Once the investigator has established a set of anticipated consequences, she tests these. This involves submitting ideas, as hypotheses, to evaluation on the basis of documented, existential results. Those hypotheses that 'pass the test' are confirmed; those that do not are jettisoned or reconstructed. The determination of a previously indeterminate situation—a situation that is felt, rather than abstracted—is the termination proper of inquiry.

This logic of inquiry applies equally to both common-sense and scientific inquiries. What distinguishes these is not the general method or pattern of inquiry. In both, we experiment; we feel an indeterminate situation; we articulate a problem; we develop anticipated consequences that are then formed into hypotheses; and we test these hypotheses in existential settings. Successful hypotheses are those that satisfy or otherwise determine an indeterminate situation. However, scientific inquiries differ from common-sense inquiries in a number of ways, some of more and some less import; the greatest difference, aside from the contexts in which scientific inquiries operate (often under laboratory or otherwise rigorously controlled environmental conditions), is the level of abstraction common to them (LW 12, 119). Common-sense inquiry and the conclusions it develops very often end in habit formation—a stock of habits is built up that we then use in solving our day-to-day or otherwise mundane problems. These habits are used as well in scientific inquiry; they provide the basis for further psychomotor (in the case of experimental manipulation of phenomena) and conceptual (in the case of objects under investigation) development. However, scientific inquiry must also avoid as much as possible becoming routine, as it then promotes the tendency to complacency, with the result that it overlooks crucial steps in experimentation or changes in phenomena. Even time- and experience-tested habits, including psychomotor skills and habits of thought, must be amenable to reconstruction in scientific inquiry.

It will do to examine some of the differing features of scientific inquiry. Here, I will look at four critical features of scientific inquiry that are self-consciously articulated in Dewey's *Logic: the Theory of Inquiry*: induction and deduction; the nature of propositions; theories, laws, and causality; and the role of mathematics and symbols. In terms of induction and deduction, Dewey tells us:

> Whatever else the scientific method is or is not, it is concerned with ascertaining the conjunctions of characteristic traits which descriptively determine kinds of relation to one another and the interrelations of characters which constitute abstract conceptions of wide applicability…The methods by which generalizations are arrived at have received the name "induction:" the methods by which already existing generalizations are employed have received the name "deduction...." Any account of scientific method must be capable of offering a coherent doctrine of the nature of induction and deduction and of their relations to one another, and the doctrine must accord with what takes place in actual scientific practice. (LW 12, 414)

With induction, we generalize a set of common characteristics, features or attributes. We take the conclusions from those generalizations and we infer what must be the case on the basis of these. Dewey calls the typical understanding of induction 'a psychological process' in which we are 'induced to apprehend universals which have been necessarily involved all the time in sense qualities and objects of empirical perception' (LW 12, 419). In calling the typical understanding of induction a 'psychological process', Dewey means to distinguish his understanding of it from this. Whereas induction is typically understood as the movement of particular to universal, this is heavily qualified by Dewey. 'Induction I take to be a movement from facts to meaning; deduction a development of meanings, an exhibition of implications, while I hold that the connection between fact and meaning is made only by an act in the ordinary physical sense of the word act, that is, by experiment involving movement of the body and change in surrounding conditions' (MW 13: 63). Elsewhere, Dewey says induction is an 'existential determination' (LW 12, 478); he also calls it a determination of meaning(s) (MW 13, 63). 'They make possible the operation of mathematical functions in deductive discourse' (LW 12, 478). In induction, we grasp what is general in the existential situation through examination of the sense qualities of that situation. Dewey calls the generalizations we develop in induction 'generic propositions' (LW 12, 253). These are propositions of kinds or classes. For example, the generalization of the class, 'liquid', consists in all of the like phenomenal attributes or characteristics that are grouped together under this rubric.

In induction, we have 'the complex of experimental operations by which antecedently existing conditions are so modified that data are obtained which indicate and test proposed modes of solution…' (LW 12, 423). Induction draws generalizations from the existing phenomena culled from the existential situation, which are then transformed into hypotheses that are actively brought to bear on the existing phenomena. This generalization, or generic proposition, then takes the form of an 'If-then' statement—what Dewey calls a 'universal conception' (LW 12, 253). In deduction, on the other hand, we make inferences on the basis of the conclusions of hypotheses we generate (LW 12, 422). There is thus 'a functional correspondence' between induction and deduction. 'The propositions which formulate data must, to satisfy the conditions of inquiry, be such as to determine a problem in the form that indicates a possible solution, which the hypothesis in which the latter is formulated must be such as operationally to provide the new data that fill out and order those previously obtained' (LW 12, 423).

As we have noted, if-then conceptions are claims about what will happen to phenomena under certain circumstances. Though they make claims on behalf of phenomena, they are symbolic, rather than referring to phenomena through existential operations. There is yet another class of propositions, a class that operates at a level of abstraction from these; Dewey calls these 'abstract conceptions' (LW 12, 258). Abstract conceptions help to regulate our universal conceptions. As such, these operate *deductively*, rather than inductively. An example will be helpful here. Consider the following if-then claim:

> I hypothesize that all liquids of the kind (an existential proposition) H_2O will evaporate (an abstract concept) over time T when the temperature (an abstract concept) rises above 100 C.

This hypothesis relies on abstract concepts: evaporation and temperature. Abstract concepts do rely on propositions for their content (e.g. we need to know what physical characteristics water consists of at a given temperature); however, the concept is itself an abstraction that relates only to other concepts (such as evaporation). As such, we can assess abstract concepts in one of two ways: the first is how well they hang together with other abstract concepts (such as the case with evaporation and temperature); the second is how well they help to generate working generic propositions (such as the hypothesis above). When we assess abstract concepts in terms of their ability to relate with one another, we are testing deductively.

Some conceptions are simple and concrete. These Dewey calls conventions. It is a convention, for example, not to place your open hand over a flame. Other conventions consist in particular propositions we use for carrying out experiments; for example, 'when attempting to ascertain the degree of evaporation of water in your experiment, be sure to fill the beaker half way for each attempt to maintain consistency across experiments'. However, though they are obviously important, conventions serve scientific inquiry only in the most mundane matters. Far more important for scientific inquiry are 'hypotheses and their meanings', which are 'developed in ordered discourse, observation and assemblage of data…'. Otherwise, 'observation and assemblage of data are carried on at random' (LW 12, 428). Dewey calls these clusters of hypotheses 'theories' (LW 12, 428). Theories rely on both abstract and generic conceptions and are formed when sets of these are banded together into a general claim about a range of phenomena. So, for example, the theory of natural selection encompasses both abstract concepts (various concepts relating to organelles, tissues and organs; various concepts of change across species; various environments), together with universal conceptions (hypotheses that must have been provable for a theory of natural selection to arise) and existential propositions (classes of fauna used in formulating universal conceptions). Laws concern interactions and interrelations that allow a 'comprehensive system of characters'. This in turn allows for 'ordered discourse' to be possible (LW 12, 439). So, for example, Boyle's Law, Charles's Law, Henry's Law and other gas laws are laws precisely because they concern the interactions of the content of the qualitative traits that determine the relations (say, increases or decreases in volume or pressure of gases, gases coming out of solution, etc.) under investigation.

Causation is a particular type of regularity. It is a means of instituting a single, unique, continuous history of events under investigation, rather than a claim for a fixed and final sequence of occurrences (LW 12, 440). For example, consider the law

> All liquids of the kind (an existential proposition) H_2O will evaporate (an abstract conception) over time T at temperature (abstract conception) X, if certain circumstances hold (result of universal conception).

The law denotes the events that take place when qualitative traits are so ordered through propositions and conceptions to render them amenable to a continuous historical series.

Dewey is keen, however, to insist on the absence of fixity or finality with respect to laws or causality. 'The fallacy vitiating the view that scientific laws are formulations of uniform unconditioned sequences of change arises from taking the function of the universal [if-then] proposition as if it were part of the structural content of the existential [classes] propositions' (LW 12, 439). If we mistake the universal conception (the proposition that tells us what we can expect under existential conditions) with the propositions of classes actually used in carrying out the particular experiment, we will mistake regularity under strict scientific conditions for a fixed and final regularity.

Finally, scientific inquiry uses symbols and mathematics to a far greater degree than other forms of inquiry. These are tools and have arisen out of the various attempts at solving existential problems (LW 12, 392). Symbols and mathematics operate at a realm distinct from the existential and the generic; indeed, they are wholly abstract. 'When, however, discourse is conducted exclusively with reference to satisfaction of its own logical conditions, or, as we say, for its own sake, the subject-matter is not only nonexistential in immediate reference but is itself formed on the ground of freedom from existential reference of even the most indirect, delayed, and ulterior kind. It is then mathematical' (LW 12, 393). However, symbols and mathematics are not fixed and final things in themselves, nor are they pure forms in some Platonic universe. They *are* abstract, and they do *not* generally participate in existential contexts; however, they have both their genesis and their purpose(s) in existential inquiries. Not only this, but they must operate to generate workable universal conceptions that can then order existential phenomenon, as Dewey says, 'The necessity of transformation of meanings in discourse in order to determine warranted existential propositions provides, nevertheless, the connecting link with the general pattern of inquiry' (LW 12, 393).

75.5.5 Scientific Inquiry and Social Science

Of central import to scientific inquiry is that it be of use in solving human problems. All inquiry takes place in social contexts, the contexts of human relations (LW 12, 481). What Dewey thinks is wrong with certain scientific research programmes is the failure to reinsert the results of scientific experimentation back into the existential conditions out of which all inquiry arises. Certain fields and programmes have become so esoteric as to have fractured the connection between findings and the existential situations out of which these findings emerged. (Logical positivism is one example of this.) This is to be deplored for Dewey; scientific research has an obligation to help aid in the solution to social problems, nowhere more so than with respect to the social sciences. Classes in particular are often treated as if they were universal conceptions, with the result that they are rendered fixed and final. In these situations, 'At best, inquiry is confined to determining whether or not objects have the traits that bring them under the scope of a given standardized conception—as still happens to a large extent in popular "judgments" in morals and politics' (LW 12, 264). Some of this state of affairs is due to the faulty methods which the social sciences pursue. Dewey admits the social sciences do not as yet possess the sophistication of methods and techniques common to the physical and natural sciences.

Dewey puts the matter this way: ‘The question is not whether the subject-matter of human relations is or can ever become a science in the sense in which physics is now a science, but whether it is such as to permit of the development of methods which, as far as they go, satisfy the logical conditions that have to be satisfied in other branches of inquiry’ (LW 12, 481). The existing methods of the social sciences have yet to allow for the logical conditions of the particular inquiries therein to be as rigorously developed and articulated as those in the physical and natural sciences.

However, it should not be concluded that the logical conditions themselves are different between the two kinds of inquiry. It is rather that it is much more difficult to convert the indeterminate situation in a social scientific inquiry into a determinate one than it is in a physical scientific inquiry, because of the complexity of social subject matters and the limitations of workable techniques and tools available to social scientists (LW 12, 485). Problems articulated in social scientific inquiry are ‘gross’ and ‘macroscopic’ in distinction to those in physical scientific inquiries (LW 12, 414). And though Dewey reminds that it is important to recognize and deal with ‘the physical conditions and laws of their interactions’, this is obviously not enough to go on for social scientific inquiry (LW 12, 486). New methods and techniques have to be developed to cope with the unique nature of social scientific subject matters. This cannot be a reductive social science, in which the techniques of the physical and natural sciences are transposed onto social scientific subject matters. ‘The assumption that social inquiry is scientific if proper techniques of observation and record (preferably statistical) are employed…fails to observe the logical conditions which in physical science give the techniques of observing and measuring their standing and force’ (LW 12, 492). Dewey continues, ‘Any problem of scientific inquiry that does not grow out of actual…social conditions is factitious; it is arbitrarily set by the inquirer instead of being objectively produced and controlled. All the techniques of observation employed in the advanced sciences may be conformed to, including the use of the best statistical methods to calculate probable errors…and yet the material ascertained be scientifically ‘dead’, i.e., irrelevant to a genuine issue, so that concern with it is hardly more than a form of intellectual busy work’ (LW 12, 492–493).

75.6 Inquiry and Science Education

In addition to Dewey’s claims for the importance of science and scientific inquiry in his philosophical and logical works, Dewey had a good deal to say about the role of scientific inquiry in education (see Chap. 42). As well, an increasing number of science educators have turned to Dewey to formulate better pedagogies and curricula for science education. Here, I will discuss Dewey’s claims for the role of scientific inquiry in science education; I will then turn to some of the more recent developments in science education conducted along Deweyan lines.

75.6.1 Science and Science Education

Science (and mathematics) education poses a unique and complex predicament for educators: the heightened and abstract nature of scientific findings (including the theories and laws of natural and physical science) are an impediment to learning. What makes scientific education a daunting task is not the lack of innate capabilities of children to master increasingly abstract conceptions, or various propositions; it is the haphazard way in which much science education is taught, together with the differences in background knowledge and techniques of students. A child's genuine inquiry cannot begin with such reified conclusions; rather, it must begin with simple observations and manipulation of the environment present-to-hand. 'What the pupil learns he at least understands. Moreover, by following, in connection with problems selected from the material of ordinary acquaintance, the methods by which scientific men have reached their perfected knowledge, he gains independent power to deal with material within his range, and avoids the mental confusion and intellectual distaste attendant upon studying matter whose meaning is only symbolic' (MW 9, 228). Rather than producing experts in scientific methods, the point of science education is to familiarize students with 'some insight into what scientific method means than that they should copy at long range and second hand the results which scientific men have reached' (MW 9, 229).

Dewey recommends what he calls the 'chronological method' in educating children to scientific inquiry. This is the method '…which begins with the experience of the learner and [that] develops from the proper modes of scientific treatment…' (MW 9, 228). Children are led up from simple observations and conclusions about the workings of their environment, through more sophisticated analyses and syntheses of isolated natural and physical phenomena. In these analyses and syntheses, children are encouraged to develop and apply the various forms of propositions and conceptions involved in actively ordering and controlling specific traits of phenomena under experimental circumstances. So, for example, what begins as a simple experiment to identify the conditions under which water evaporates in a puddle adjacent to the school (conditions such as a sunny day, increased temperature) becomes, as the student ages and is introduced to increasingly sophisticated techniques, an examination of the evaporation of water under strict laboratory conditions, with the use of such techniques as classes (liquids), universal conceptions (experimental hypotheses) and abstract conceptions (temperature, evaporation) and laws for liquids and gases, as well as tools for the examination of tendencies amongst large groups of phenomena, such as mathematics and statistics. Dewey surmises that if children were taught to use the 'chronological method' from the beginning of their formal education and consistently thereafter, much of the confusion that occurs in increasing the level of abstraction in science education would gradually diminish.

In order for students to engage experimentally with phenomena, they must actively engage the world around them. They must experiment with materials in various way and order and control traits of existential phenomena, beginning in a trial-and-error manner. This requires that the material to be tested have some connection to the child's life beyond the classroom. Otherwise, genuine problems—problems that are felt rather than deduced or prescribed—will not materialize. One of the best ways for this to occur is to begin scientific inquiry with available technologies and with existing social problems (MW 9, 232). Of technologies, Dewey says, 'The wonderful transformation of production and distribution known as the industrial revolution is the fruit of experimental science. Railways, steamboats, electric motors, telephone and telegraph, automobiles, aeroplanes and dirigibles are conspicuous evidences of the application of science in life. But none of them would be of much importance without the thousands of less sensational inventions by means of which natural science has been rendered tributary to our modern life' (MW 9, 232). Of social problems, Dewey has in mind the problems common to children at their particular developmental age and stage, as well as the particular problems of circumstance and context—including the barriers children face, such as those of race, class, gender and geography (MW 9, 91).

Properly conducted, inquiry in science education will begin with a 'felt difficulty'; an 'indeterminate situation' that then stimulates genuine interest. This is the crucial stage for inquiry in science education and, indeed, inquiry in all contexts. If genuine interest is not captured, any inquiry that results will be an externally motivated one certain to result in poor focus and haphazard conclusions. This problem is the child's, not the teacher's. It is a waste of time and energy for the teacher to simply pronounce on what problem the student will begin with, if the student hasn't come to see this problem on, and as, his or her own. Only with genuine interest can a problem be properly articulated so that it can satisfy the rigours of inference and testing that follow.

Once an articulated problem is produced, anticipatory consequences of acting on phenomena are put forth. This is an imaginative stage or phase of scientific inquiry, in which the student thinks through various possible courses of action. Upon deciding a course of action, the student will make use of tools of inference (as in formulating hypotheses of the 'If-then' sort, to test out specific anticipated outcomes; deduction, especially in terms of abstract concepts; induction and existential propositions of classes (all of this class or only some or none of this class). These are tools in the experimental phase of the inquiry that are put to work in order to achieve the desired outcome. Depending on the nature of the experiment and the tools and techniques available to the students, more or less attention will be spent on making this phase of the experiment and the tools of inference that belong to its self-conscious. Some of these tools and techniques can be taught and discussed; however, to be of value to the student in her experimentation, they must be developed and worked through *in* the experimentation.

Finally, if the experiment is successful, resolution or closure of the indeterminate situation takes place. Again, this is a felt, as opposed to abstract, resolution. Successful termination of scientific inquiry does not merely end in the 'right' result, or to the satisfaction of the teacher. On the objective side, it ends with the successful settlement of the indeterminate situation; on the subjective side, it ends when the student experiences a qualitative closure of the situation or event. Unless and until this qualitative closure or termination takes place, inquiry is not complete. And if inquiry is not complete, the impetus for further investigation that arises as a result of the satisfaction of having closure of an indeterminate situation is denied. Closure is the ‘aha’ moment when an experience is at its most satisfying. And this is the moment of genuine growth. To deny or otherwise not conclude with this moment is to blunt the motive force for future scientific inquiries.

However, Dewey recognizes that these changes to the structure and content of science education are not, by themselves, enough; differences in background knowledge are another matter entirely. These cannot be so easily remedied and require changes in existing social and political realities—realities that have resulted in the barriers of race, class and gender and lack of education that keep some disenfranchised (MW 9, 91). Unfortunately, individual schools are hampered in their ability to mitigate circumstances such as poverty, racial and gender bigotry and socioeconomic divides. Inquiry, though inestimably important to students’ intellectual development and their capacity to solve problems, needs to be heavily supplemented with cooperative social institutions and programmes if it is going to overcome the paucity of genuine intellectual growth that results from social barriers and divides.

75.6.2 Deweyan Inquiry and Constructivism in Science Education

Dewey has been a central figure in the great mass of scholarship written on behalf of constructivism in science and science education (Von Glaserfeld 1984, 1998; Phillips 1995; Garrison 1995, 1997a; Vanderstraeten 2002; Kruckeberg 2006; Gordon 2009). While some are content to note Dewey’s historical influence on later philosophers (such as Richard Rorty) is squarely in line with constructivist beliefs and others are content to point out that Dewey’s anti-metaphysical insistence in matters of knowledge is of a piece with their constructivist values, still others have gone further and developed Deweyan accounts of constructivism. Here, I will examine briefly constructivism in science education, noting how and where Dewey is invoked. I will then turn to a very brief exposition of three accounts of Dewey in the name of constructivism and science education: Ernst Von Glasersfeld’s ‘radical constructivism’, Jim Garrison’s ‘social pragmatic constructivism’ and Raf Vanderstraeten’s ‘transactional constructivism’.

It will do to outline briefly the thinking behind the constructivist movement in education. Constructivism is a label for a variety of various, like-minded models of cognition and knowledge that share a history, as well as a central tenet: the rejection of metaphysical realist and empiricist theories of knowledge, often in favour of developmental and transactional accounts that stress the organism of person’s own role in knowledge acquisition (LaRochelle and Bednarz 1998, p. 7). In education there are ‘radical constructivisms’, ‘pragmatic social constructivisms’, ‘didactic constructivisms’ and ‘poststructuralist constructivisms’, amongst others. Dewey’s involvement in constructivism comes largely as a result of his own rejection of metaphysical accounts of knowledge creation and production. Inquiry in constructivist accounts of science education invoking Dewey generally stresses the anti-metaphysical and anti-dualist dimensions of his thinking in their respective projects for science education. However, some thinkers have been compelled to go further and investigate the particular areas where Dewey's account of knowledge creation and production reaches beyond complementarity with existing understandings of constructivism in science education to form a distinctive constructivism in its own right.

Both Garrison and Ernst Von Glasersfeld draw on Dewey in their respective understandings of constructivism, and it will do to discuss their differences. Von Glasersfeld considers himself a 'radical' constructivist, a position Von Glasersfeld says he owes to Kant, Piaget and the notion of 'variability'—the idea that all conceptual schemes are premised on their utility or purpose (Von Glaserfeld 1984, p. 12). Von Glasersfeld appropriates certain of Kant's understandings to elaborate his own articulations of conceptual schemes. For example, Von Glasersfeld appropriates Kant through saying his understanding of reciprocity (as discussed by Kant as the Third Analogy of Experience) is beneficial to understanding how shared conceptual schemes develop. In the Third Analogy, 'All substances, insofar as they can be perceived in space as simultaneous, are in thoroughgoing interaction' (Kant 1998, p. A 211). This has obvious utility to Newton's third law of motion. And it has utility as well to Von Glasersfeld, who quotes Kant approvingly; 'It is manifest that, if one wants to imagine a thinking being, one would have to put oneself in its place and to impute one's own subject to the object one intended to consider…' (Von Glaserfeld 1998, p. 124). This 'reciprocity', analogized further from Kant's Third Analogy, is said by Von Glasersfeld to be akin to how we develop our shared, conceptual schemes. Von Glasersfeld does not intend to claim Kant's understanding and use of reciprocity as completely his own; he is rather content to accept the analogy and turn to empirical factors such as adaptation to understand constructivism. His is a "cognitive constructivism," which also has its locus in the seminal works of Piaget. Yet, this 'cognitive constructivism', as a theory invoking the transcendental substrates of Kant, sharply distinguishes Von Glasersfeld's project from empirically inclined projects such as Garrison's (Grandy 1998, p. 115).

Garrison's account of Dewey's 'pragmatic social constructivism' presents Dewey as a social behaviourist who is inimical to mental representations (Garrison 1995, p. 717). While Garrison clearly endorses a Dewey that evinces a strong role for natural (non-mentalistic) conceptions, his endorsement does not extend to wholly subjective or mentalistic representations, which he sees operating in Von Glasersfeld's account of 'radical constructivism'. Garrison's Dewey stresses language as a social construction, together with 'dialogicality and multiple authorship' (Garrison 1995, p. 727). Unlike Von Glasersfeld's understanding of constructivism, Dewey's account is anti-dualist and anti-subjectivist (Garrison 1997a, p. 305). Indeed, Dewey's theories of mind and meaning were *entirely* behaviourist (Garrison 1995, p. 725; 1997a, p. 308), and mind for Dewey was entirely a social construction. Social behaviour—the behaviour existing between and within social units—transforms organic behaviour as a result of (shared) language into meaningful behaviour (Garrison 1997a, p. 308). Garrison claims that rather than focusing on traditional epistemic tasks, education and science education in particular should be attempting to construct stronger models of dialogicality and promote active listening.

Vanderstraeten's account of Dewey's 'transactional constructivism' begins with an analysis of Dewey's organic account of coordination and perception (Vanderstraeten 2002, p. 236). This leads to an analysis of habit, to thinking and to knowledge formulation and the ways these form an integral whole. Communication (as with Garrison) is key in all of this. Education is a means of communication and education is 'a participatory, co-constructive process' (Vanderstraeten 2002, p. 241). Objects and practices acquire shared meaning because they are part of larger and shared sets of experiences (Vanderstraeten 2002, p. 241). Knowing is an active construction that takes place in the organism-environment transaction. This Vanderstraeten contrasts to Von Glasersfeld's 'radical constructivism', which he seems to see as insufficiently 'deep' to thwart the accusations that it is one more example of an account of correspondence to reality (Vanderstraeten 2002, p. 243). Garrison and Vanderstraeten thus both share an antipathy towards mentalistic representations and a regard for a 'transactional' accounting of constructivism in education.

It is difficult to evaluate the various constructivisms developed in Dewey's name. They clearly concentrate on central themes and concerns of Dewey and to do so is correct. The focus on transaction of the child and environment and the social dimension(s) of experience are vitally important to any further pedagogy of science, as is the stress on communication and dialogue. Beyond this, it is unclear how helpful it is to include Dewey in the pantheon of constructivists, let alone develop a constructivism from his various educational and philosophical writings. While Dewey shares many of the intellectual proclivities of other constructivists (including constructivist science educators), it remains to be seen what tangible benefits to science education come from including Dewey in this pantheon. Much if not most of the work in constructivism is content to present accounts of Dewey that do little to advance our understanding of him beyond what has elsewhere been articulated.

I attribute much of this lack of advance to the superficial nature of the readings of Dewey. In my opinion, seldom do constructivists dig deep enough to reveal the connections between Dewey's theories of knowledge and logic and his theory of aesthetic experience, to say nothing of his social and political writings (Garrison is the exception, here). More problematically, running Dewey together with Kant and Piaget as Von Glasersfeld does serves to mask tremendous underlying differences in their respective epistemologies: if Kant, as a transcendentalist, was a constructivist and Dewey, as a naturalistic empiricist, was a constructivist, it becomes a huge task to explain what foundation constructivism rests upon. Sadly, most constructivists (Garrison is again the exception) do not probe the foundations, and the resultant constructivisms they champion are but castles made of sand (see Chap. 31).

75.6.3 Dewey and the Science Curriculum

Dewey's written output while serving as the head of the University of Chicago Laboratory School (1896–1903) is well known to most educators. It includes *School and Society* (1899) as well as numerous monographs on various aspects of pedagogy and curriculum. Additionally, historical, biographical and philosophical work on the Laboratory School (Camp Mayhew and Camp Edwards 1936; Wirth 1979; Tanner 1997; Johnston 2006) has invoked inquiry directly. Recently, curriculum leaders and scholars have developed novel understandings of science education with a strong role, if not a focus, for inquiry to play. I will discuss some of these further.

Inquiry has become a dominant theme in science education (Rudolph 2005, p. 43). Aside from its logical features, this generally extends to 'hands-on' manipulation of objects, the emphasis on 'real world' activities and the use of associated technologies. As well, projects, where a number of related exercises are undertaken as part of a larger curricular whole, are often stressed. The continuity between a child's past experiences and those the teacher wishes the child to undergo is also maintained (Howes 2008, p. 538). Models of science education for early childhood education that propose drawing on a child's basic impulses to create further situations for the development of intelligent dispositions and skills have also been developed (Howes 2008, p. 538). Beyond this, more specific accounts of Dewey's holism and particularly how science and science education merges with art and aesthetic experience in an organic accounting have been offered. These latter accounts have been developed simultaneously by philosophers of education (Garrison 1997) and curriculum scholars such as those working at the Dewey Ideas Group at Michigan State (Wong and Pugh 2001; Girod and Wong 2002; Pugh and Girod 2007). All stress the importance of inquiry in regards to science education.

Garrison stresses the importance of aesthetic experience and particularly the precognitive background we draw upon when we inquire (1997b, p. 101–102). The logics that we use when we solve educational problems rely on this precognitive background and inform them. Garrison's point is to underscore the situation-specific nature of logic; there is no one logical method right for all situations; the situation itself will very often dictate what logical processes are to operate (Garrison 1997b, p. 98). Attention to the background conditions of experience, as well as the particular experience a child forms, is thus vital for science educators if they are to gauge successfully the student's learning.

Wong, Girod and Pugh also stress the precognitive dimension of experience. This drives instrumental understanding and forms the context out of which instrumental understanding operates (Girod and Wong 2002, p. 200). Like Garrison, these scholars concentrate on the motivation for learning in the first place, rather than the specific logical steps or processes undertaken. This necessitates concentrating on the experiences students have, rather than the outcomes of the particular lesson. A focus on the relationship between the concepts and ideas developed in the lesson and the experience the student has, together with attention to the satisfaction and interest inherent in genuine experiencing, is key (Pugh and Girod 2007, p. 14–16). Aesthetic experience is at once the highest and deepest of the forms of experience had and undergone. Helping to bring a child to have an aesthetic experience involving scientific experimentation is to ensure that genuine learning is taking place. Doing so releases the 'transforming' and 'unifying' elements of aesthetic understanding (Girod and Wong 2002, p. 208). The satisfaction had in having and undergoing the aesthetic experience of a scientific experiment through all of its phases is the basis for the development of real, as opposed to merely rote, knowing. Thus, in crafting science lessons, aesthetic experience must be borne in mind. This is not to say that other forms of experience are valueless; however, facilitating an aesthetic experience is the surest means to the 'teachable moment' that teachers value above all.

75.6.4 Dewey and the Teaching of Science

Problem-solving, discovery and inquiry methods are popular and well represented in theories of teaching science, in part due to Dewey's role in connecting his theory of inquiry to educational situations and events (Glassman 2001). All of these methods insist on taking the needs, desires, attitudes and developmental ages and stages of students as primary in the facilitation of science education, rather than teaching the discipline as a coherent subject matter (Eshach 1997). Concentrating on students' experiences rather than on the dissemination of the subject matter, together with a focus on the active role played by students in investigating natural phenomena, is paramount. This insists the teacher manipulate the environment to help facilitate the students' experiences such that they can actively inquire, in the manner of the stages of inquiry Dewey discusses in *How We Think* and elsewhere.

This facilitation of experiences also insists on conducting science in a manner similar to how scientists conduct it themselves, in their experimental investigations. Science, as Dewey insists, does not occur in isolation: nor should science education. The scientific investigation of natural phenomena is most clearly reproduced when students work in teams or groups, conducting an inquiry from beginning to end (from the first to the final stage of inquiry), rather than learning isolated facts or formulae from a textbook. Models of cooperative learning often cite Dewey as an early exponent (e.g. Brown and Palincsar 1989, p. 397–398). Furthermore, scientific investigation demands corroboration of results and not simply the findings of an isolated experiment (Eshach 1997). Writing up results and (re)testing them are as vital to science as the initial experimentation, and both must be included in a programme of science education. This might include both whole-class discussion and the writing of novel 'texts', particularly in the elementary grades (Howes 2008, p. 545).

Recently, it has been suggested that Dewey's understanding of scientific inquiry and science education be utilized to help integrate existing rival theories such as constructivism and objectivism under the rubric of scientific literacy (Willison and Taylor 2009, p. 32). It is argued that this may help resolve some of the tension that keeps at bay the practical advices nesting in the various theories. Dewey has also been invoked in the ongoing debates about the role of science education in the overall preparation of students: while the standards-based push to increase scientific subject matter and instructional time in public schools is laudable, it is also the case that what gets pushed first is very often abstract concepts, formulae and principles at the expense of context and experimentation (Rudolph 2005, p. 806; Chinn and Malhotra 2002, p. 199). Dewey's understanding of the contexts of scientific inquiry is a valuable corrective in this regard.

75.6.5 Overall Assessment of Dewey's Role in Science Education

Deweyan models of science education have been helpful, particularly in stressing the cooperative nature of learning, the experimental nature of knowledge acquisition and the aesthetic dimensions of children's' experiences. It makes good theoretical sense to concentrate our attention on issues of interest, motivation, satisfaction and other 'traits' of experience that bookend inquiry in science education. Furthermore, invoking Dewey, scholars and practitioners have developed comprehensive models of science education that do not resemble cookbooks or 'how-to' manuals (or lists of objectives and standards). As well, they have contextualized intellectual tools such as concepts, ideas, algorithms and processes. Rather than being set off from the curriculum or subject matter, inquiry is now thoroughly integrated in these models. And rather than being a procedure that is separate from the child or a set of steps or stages the child must plod her way through, inquiry is now seen as a process involving her experience throughout.

However, much of the scholarship on Dewey in science education has been content to draw on Dewey in so superficial a fashion that little of Dewey's actual logical, epistemological or experiential philosophy has been adequately mined. What remains for science educators using Dewey's philosophy of education is to further connect Dewey's theories of experience and art with his theory of logic—especially the accounts of propositions and conceptions he details in *Logic: the Theory of Inquiry*. A suitably comprehensive account of Deweyan inquiry for science education (one that integrates both experience and the tools of logical inquiry) has yet to be fashioned. Beyond this, educators must do a better overall job of convincing sceptics (and there are many) that think Deweyan-inspired methods of science education will reap advantageous results. To give but one example, criticisms regarding the bracketing or ignoring of psychological research that indicates the importance of working memory have been raised against constructivism and inquiry-based teaching:

> Any instructional theory that ignores the limits of working memory when dealing with novel information or ignores the disappearance of those limits when dealing with familiar information is unlikely to be effective. Recommendations advocating minimal guidance during instruction proceed as though working memory does not exist or, if it does exist, that it has no relevant limitations when dealing with novel information, the very information of interest to constructivist teaching procedures. We know that problem solving, which is

> central to one instructional procedure advocating minimal guidance, called inquiry-based instruction, places a huge burden on working memory….The onus should surely be on those who support inquiry-based instruction to explain how such a procedure circumvents the well-known limits of working memory when dealing with novel information. (Kirschner et al. 2006, p. 77)

These concerns are to be taken seriously. As these are empirical concerns, they must be addressed empirically. To address these means not simply providing a re-articulation of Dewey's texts (though this is valuable initially); rather, further articulation of Dewey's understanding, further articulation of the application of Dewey's understanding of science and science education to various teaching practices and further empirical verification of this reconstructed articulation through experimental design must be demonstrated. In other words, the way to address these concerns is through following the stages of inquiry from articulation of the problem to hypothesis testing and the formation of anticipated consequences (the formation of universal conceptions), to rigorous testing (using the 'tools' of induction and deduction, as well as the construction and invocation of abstract concepts) and to evaluation in the empirical setting in which the problem is first felt and articulated. Following the lines of Dewey's theory of inquiry is the only reasonable way to reveal problems with the empirical investigations undertaken in the quest to confirm or disconfirm claims on behalf of inquiry, discovery or problem-solving methods.

75.7 Conclusion: Dewey and Science Education

Dewey has and doubtless will continue to provide fertile ground for explorations into various dimensions of scientific inquiry and science education, including pedagogy and the curriculum. Dewey's account of inquiry offers advantages other accounts very often lack: it is holistic, context-bound and self-correcting; it is rooted in experience and the generic 'traits of existence' that arise out of the transactions of human beings and their environments (including the 'social' environment of other people). Yet, it is rigorous in its logical processes, with a strong and detailed accounting of conceptions, ideas, proposition and other logical functions. Historically, it has been vitally important for various accounts of pedagogy and curriculum.

The state of Deweyan scholarship on science education is another matter; as it stands, Dewey scholarship in science education repeats many of same mantras as Dewey scholarship in other areas of education: the importance of inquiry, discovery and problem-based methods and pedagogies; group, cooperative and team-oriented projects; and an emphasis of experimental learning over and against disciplinary or subject matter learning (at least for the elementary grades). However, it has not progressed much beyond these, despite the invocation of Dewey in constructivism and other fashionable models of teaching and curriculum. In my opinion, what is necessary for further scholarship is to develop a cogent model of Deweyan inquiry for science education that integrates Dewey's accounts of experience and art with his detailed account of the functions of logical inquiry, including the tools of conception, propositions and symbols. Doing so requires us to dig deeper into Dewey's logical, epistemological and experiential theories than is usually done. A few scholars (e.g. Garrison) have begun this scholarship, but much more work on the part of the Deweyan community of scholars remains. A systematic model of science education that is attentive to logical, epistemological, experiential and social-political as well as educational concerns will be of inestimable value for further pedagogical and curricular claims on behalf of science education. Beyond this, it remains to be seen whether any of these accounts of science education invoking the name or scholarship of Dewey are able to penetrate the morass of objectives-driven 'standard' science education.

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Chapter 76
Joseph J. Schwab: His Work and His Legacy

George E. DeBoer

76.1 Introduction

Most science educators are familiar with Joseph Schwab because of his contributions to the school reform movement in biology in the United States in the 1960s, especially through his connection to the Biological Sciences Curriculum Study (BSCS) (see, e.g., DeBoer 1991). Schwab brought terms like "rhetoric of conclusions" and "narrative of enquiry"[1] to the discussion of school science, and he contributed to the reform of science education as chair of the Teacher Preparation Committee at BSCS and as author of the *Biology Teachers Handbook* (Schwab 1963a). But most of Schwab's work in science education was not focused on the school curriculum, rather on the undergraduate science program while he was on the faculty at the University of Chicago. His ideas about the nature of the science curriculum were shaped as he and his colleagues at Chicago worked out the details of a comprehensive program of general education[2] for the undergraduate college. It was at Chicago that his professional career began and where it ended 36 years later, and it was at Chicago that he thought and wrote about science education, first for undergraduate students and then later as part of the precollege science curriculum reforms of the 1950s and 1960s.

Joseph Schwab was born in Columbus, Mississippi, in 1909; matriculated as an undergraduate at age 15 at the University of Chicago in 1924; and graduated with degrees in physics and biology in 1930. He earned a doctorate in genetics from

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[1] Schwab preferred "enquiry" to "inquiry," but in his writing the spelling varies depending on where the work was published. In this chapter, the spelling that actually appeared in a publication will be used, and all my discussions of his work will use the word inquiry.

[2] The terms *general education* and *liberal education* will be used synonymously in this chapter to describe nonspecialized and nonvocational programs of study that offer students a broad base of experience with various modes of thought and knowledge of their culture.

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Chicago in 1939. In 1937, he spent a year at Columbia University Teachers College, where he was influenced by both John Dewey and Ralph Tyler. Schwab came to Chicago as an instructor in 1938, and he retired as professor of education and the William Rainey Harper professor of natural sciences in 1974. He then joined the Center for the Study of Democratic Institutions, founded by Robert Maynard Hutchins, in Santa Barbara, California, where he continued to think and write about curriculum. He died in Lancaster, Pennsylvania, in 1988.

He began his graduate work at Chicago just as Hutchins was beginning his long tenure, first as president (1929–1945) and then as chancellor of the university (1945–1951). This was also the time that the college was beginning to embark on its decadelong experiment in general education. Hutchins was a vigorous advocate of the Great Books approach to general education and a promoter of liberal education as the best preparation for informed, responsible citizenship (Hutchins 1936). Hutchins believed that undergraduate education should focus on a student's intellectual development through a careful study of classic works of Western civilization, taught through a dialectical Socratic method, rather than on the development of practical skills and professional training, which tended to characterize higher education at that time. His approach was intended to develop citizens with the independence of mind suited for life in a democratic society. The study of a core body of great works would also provide a common educational experience so that citizens could communicate beyond their areas of specialized interest.

Hutchins was joined in 1930 by Mortimer Adler and, with Adler, went on to found the Great Books of the Western World program and the Great Books Foundation in 1947 (http://www.greatbooks.org/about/history). But the faculty rejected Hutchins' plan for a Great Books approach for the undergraduate college, and the program never became the model of undergraduate education at Chicago that it did at St. John's College in Annapolis, Maryland. However, its focus on the intellectual heritage of Western civilization did influence the spirit and forms the general education program took at Chicago, and the approach was used in the university's adult evening extension college, which Schwab chaired when he joined the faculty in 1938.

Although Schwab's primary interest and responsibility was organizing the science curriculum for the general education program at Chicago, the integrative nature of general education also gave him opportunities to think about the role of the social sciences and humanities in general education and the boundaries between those subject areas and the sciences. He had a passion for psychology, social sciences, religion, and humanities, and he addressed issues from these disciplines in his writing on education. In addition to being a member of the science faculty, Schwab was also a respected education theorist. In 1949 he was appointed to the university's education department, where he taught courses in the philosophy of education. And later he did curriculum work at the Melton Research Center of the Jewish Theological Seminary, where he helped develop materials to teach character education to students attending Jewish summer camps.

He had an especially strong interest in psychoanalysis, undergoing analysis himself. In *Eros and Education* (1954) Schwab wrote about the nature of the interactions between faculty and students during classroom discussions from a Freudian perspective. In the late 1950s and early 1960s, his attention shifted to the school science curriculum reform movement through his work with BSCS. In 1969, his attention shifted back to higher education as the student protest movement gained momentum. In response to the protests, he published the *College Curriculum and Student Protest* (Schwab 1969a), in which he focused again on the role of liberal education in society, especially on ideas of "community, of moral choice, and of deliberation and decision-making" (Westbury and Wilkof 1978, p. 30). His final contributions to the field of education were to curriculum development in general. Through a series of papers on the advantages of a practical rather than theoretical approach to curriculum study, he became well known among curriculum theorists for his claim that "the field of curriculum is moribund" (Schwab 1970, p. 1).

76.2 The Undergraduate College at Chicago

Throughout the 1930s, a group of University of Chicago faculty pressed forward on a plan to create a coherent and well-integrated approach to general education for the undergraduate college. In 1937, a four-year program of undergraduate study, completely devoted to general education, was officially approved by the university (Schwab 1950a). When Schwab joined the faculty in 1938, he took a leading role in the development of the science component of the program as chair of the natural sciences sequence in the undergraduate college, and it was his efforts to conceptualize that program to which he devoted most of his professional career.

The early to mid-twentieth century was a time of vigorous debate about the role of undergraduate education at colleges and universities in the United States. At its beginning, higher education in the United States had had a classical character, with a focus on classical literature and languages. But by the mid to late nineteenth century, the model of the German university, with its emphasis on specialization and empirical investigations in the sciences, began to take hold in the United States and elsewhere. By the late nineteenth century, that model began to predominate in universities like Chicago. As Daniel Bell put it:

> The American university, as it emerged in the latter decades of the nineteenth century, brought with it a new religion of research. Even scholarship in the traditional disciplines was conceived, within that purview, as being concerned with detailed and specialized problems. The reaction of the liberal arts college was to strike out against specialism. (Bell 1966, p. 51)

Questions began to be raised in universities across the United States about the appropriate role of the undergraduate experience, coming as it does between the high school and the professional and graduate schools: Should the undergraduate years be spent in preprofessional training for those planning to enter the professional schools, should it focus on early scholarly preparation for those going on to graduate school, or should it simply be preparation for informed citizenry? What, if any, is the importance of having students develop an appreciation for the cultural artifacts that the society thinks a cultivated person should be familiar with, to become aware of basic principles that guide moral behavior, or to gain an understanding of how knowledge is organized and revised? And how important is it for citizens in a democratic society to have a shared intellectual experience that provides them with a common ground for deliberation and debate regardless of their life work or specialization? These were the questions that were being debated.

The programs of general education being developed at Chicago, along with those at places like Columbia and Harvard, became models for colleges throughout the country. (See Bell (1966) for a discussion of the Chicago, Columbia, and Harvard experiments in general education.) Although these programs differed in detail, they all had a commitment to certain general principles and purposes. As Bell said in his study of general education, the function of a general education program in the undergraduate college was:

> …to teach modes of conceptualization, explanation, and verification of knowledge. As between the secondary school, with its emphasis on primary skills and factual data, and the graduate or professional school, whose necessary concern is with specialization and technique, the distinctive function of the college is to deal with the grounds of knowledge: not *what* one knows but *how* one knows. The college can be the unique place where students acquire self-consciousness, historical consciousness, and methodological consciousness. (Bell 1966, p. 8)

General education programs such as this had as their stated purpose the development of enlightened and responsible citizens for life in a free society. They emphasized personal growth and individuality and a universal rather than a provincial or nationalistic world view. Programs usually focused on the humanities and classics, particularly the study of Western civilization, and they avoided connections with utilitarian and vocational aims and with career preparation. But programs were not all the same. They differed in the emphasis they placed on developing moral men and women versus providing students with a broad understanding of multiple ethical perspectives, the importance they placed on learning about the heritage of the society versus studying the contemporary world, and how much they valued the acquisition of a broad base of knowledge across the curriculum compared to providing students opportunities to develop skills as independent thinkers.[3]

For example, the stated purpose of the Chicago program was to develop the intellect. It was not primarily about the knowledge one acquired, but rather the ability to think, to contemplate, and to consider alternatives. To do that well, one had to learn about the complexities of the world in relation to each other. The most important job of the college was to introduce students to positions other than their own and to help them develop the power to form judgments. In the Chicago program, that thinking would take place in the context of cultural elements (works of art, music, literature, and science) that were deemed to be most important by society. The task of curriculum developers was to create curricular content and learning activities that allowed students to investigate these cultural elements thoroughly and in context. The Chicago program also took an analytical approach to knowledge rather than the

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[3] See *The Emergence of the American University* by Lawrence Veysey (1981) for an extended discussion of the history of the American University during the time period in question.

historical approach that often characterized general education programs. Especially in the sciences, and largely through Schwab's influence, the goal of the curriculum developers was, in Bell's words, "to find the controlling principles of 'classification' in the definition of subjects or of disciplines within fields" (Bell 1966, p. 33). Referring to the difference between these two approaches in the context of science, Bell said:

> …the question is whether one wants to emphasize historicism, with its doctrine that the understanding of an event can be found only in its unique context, or the analytical approach, which finds meaning in a phenomenon as one of a type-class, and seeks, further, a sense of invariant relationships. …Does one teach science through its history, or by analysis of its models of inquiry? (p. 62)

At Chicago, general education meant learning the special modes of conceptualization that characterized each discipline, not simply reviewing the historical development of a field. Historical texts were read and examined, but the purpose was not just to familiarize students with the knowledge these texts contained but to teach students how different forms of knowledge were created and how the students themselves could be analytical and critical of those intellectual methods and products.

At Chicago, this was to be accomplished by means of an interpretive (hermeneutic) approach in which students extracted meaning from selected written texts, pieces of music, works of art and architecture, and reports of scientific investigations, taking into consideration not only the cultural artifacts themselves but also the purposes and intentions of the creator of those artifacts. Nothing was to be taken as given, but always open to analysis and interpretation. In science, the texts that were subjected to interpretation were original scientific research papers, and the pedagogical approach for teaching them involved having students examine those papers to become familiar with the particular knowledge claims that were made, the investigative methods used, and the broader intellectual and practical contexts in which each investigation was conducted (Schwab 1950a).

The challenge that Schwab and his colleagues faced was how to create an educational experience that would lead to intellectual growth so that students would be open-minded, skeptical, able to think for themselves, and prepared to take on positions of leadership in society. The education that was envisioned emphasized the integration of knowledge from multiple disciplines and a search for and an appreciation of fundamental principles that define human experience, accomplished not through memorization but through discussion and deliberation.

But, even as efforts were under way in places like Chicago to build general education programs, the overall trend in undergraduate education was toward specialization, professional and preprofessional training, and the accumulation of knowledge. As Schwab noted, a "rhetoric of conclusions" dominated undergraduate teaching, where students were presented with knowledge of the disciplines without being required to think critically or make judgments about that knowledge. Many of these issues were addressed in the scholarly writing that Schwab was engaged in while he was the chair of the science program in the undergraduate college at Chicago, and it is to that work that we turn in the next several sections of this chapter.

76.3 The Place of Science in Liberal Education

76.3.1 A Taxonomy of Types of Science

In 1949, Schwab published a paper titled *The Nature of Scientific Knowledge as Related to Liberal Education*. In that paper he argued that all students should be exposed to the breadth and variety of science both in its content and its methods. Science should not be treated monolithically but as a complex and varied study. To accurately represent the complex nature of the physical world and the methods used to study it, liberal education should use pedagogical approaches that reflect that complexity. Diversity exists in the content and methodologies of the separate fields of science, and diversity exists in how philosophers of science view the nature of science, including the nature of causality, the nature of induction, the role of hypothesis testing, and the relationship between mathematical knowledge and the physical world. Schwab argued that because of this diversity of methods that are used and views that are held about the nature of science, no one single set of "epistemic or metaphysical presuppositions" concerning science can cover the variety of ideas that exists (Schwab 1949, p. 248). An accurate portrayal of the nature of science as part of a liberal arts education requires that this diversity of scientific methodology and interpretation be taught as fully as possible.

Schwab proposed a taxonomy of scientific investigation that could serve as an aid to the teaching of science in a general education program, both to support the choice of subject matter and how that subject matter could be examined by students. He identified four types of scientific investigations, which differ from each other in the kind of knowledge that is generated, the kind of data that are collected, and the form of validation that is used in each. The four types, which he believed encompassed most forms of scientific inquiry, were taxonomic science, measurement science, causal science, and relational or analogical science.

Taxonomic science involves the creation of classification schemes for organizing objects and events in the world. These classification schemes exist in virtually all fields of science, including the classification of disease for diagnostic purposes, categorizing living organisms to study their degree of hereditary relatedness, or the classification of types of chemical molecules on the basis of their molecular structures. All of these classification schemes were developed for a purpose, and all of them require difficult decisions at the margins. For the purpose of liberal study, "…a given taxonomic system is understood when it is seen as one of several alternatives" and when "…some of the doubtful areas of the taxonomy are seen and some of the reasons for their doubtful status understood" (Schwab 1949, pp. 255–256).

Measurement science involves measuring and relating changes in two or more objective quantities. Familiar examples include the relationship between the intensity of light and distance from the light source, the frequency of vibration of a plucked string and the length of the string, or the degree of sinking of an object and its density in relation to the density of the medium it is immersed in. For general education purposes, it is important that students understand that assumptions are made when reporting these relationships in a mathematical form, such as the assumption that there is a point source of light (which is an idealization of the real world). Students should also be aware of the possible effects of abstracting only certain variables of interest from a more complex set of related variables that could be studied.

Regarding *causal science*, Schwab argues that much of what is thought of as "causal science" can actually be placed in the other three categories, but even after doing that, there remains a separate type of investigation that deals with systems of mutually interacting and mutually determined parts acting as a whole. He cites physiological and social systems as examples. The defining features of these causal systems involve "interaction, mutual determination, and concerted action" (Schwab 1949, pp. 258). The challenge for students is to grasp the nature of the interacting parts of the system and their relationship to the whole organism or system. Of necessity, because these systems are too complex to be studied as a unity, their parts and pieces must be studied in isolation. For general education purposes, the student:

> …must be prepared to discover, in the records of such research, answers to the questions of what kinds of "parts" are being treated, what analysis of "functions" are related to the parts and functions of other related researches, and how, if at all, the researcher in question relates his discovered functions and parts to one another to constitute larger units more nearly approaching the unity of the organism as a whole. (Schwab 1949, p. 260)

Finally, Schwab identified *relational science* as a fourth type of scientific inquiry. Regarding this type of inquiry, which relies on models, analogies, and forms of representation, Schwab said:

> By "relational science" I mean those patterns of inquiry which are most fully understood as aiming toward knowledge which attempts to "explain" or "account for" matters previously known by inventing co-related quantities which do not have one-to-one correlates among the phenomena to be accounted for, or by inventing mechanisms not directly accessible to observation but so conceived and applied to the phenomena to be explained that it can be said that certain things behave *as if* these mechanisms existed. (Schwab 1949, p. 260)

These borrowed relationships of relational science, which are applied to the new observations, may come from either physical models or from abstract mathematical and conceptual models.

The educational imperative of these diverse approaches to scientific investigation is that students should have enough familiarity with them to analyze actual research studies in each category and make comparisons between them. Instruction should "…educate, encourage, and exercise the student in applying appropriate canons of comprehension and evaluation to…examples of scientific inquiry" (Schwab 1949, p. 264). This enables students to make judgments about which of a number of possible alternatives is the most appropriate approach to collecting data, drawing conclusions, and linking evidence to conclusions, which in turn will give students a more honest and accurate picture of the physical world and how it is studied. When the nature of science itself is chosen as the subject for students to study, then a variety of historical, philosophical, and methodological interpretations of science should be read, discussed, and analyzed in the same way.

76.3.2 The Tentative Nature of Science

Also key to an understanding of science for liberal education purposes was to appreciate “the ongoing, unclosed character of science” (Schwab 1949, p. 263). Yet, as Schwab observed, colleges still taught “the conclusions of science and definitive solutions to its problems” (p. 263). Teaching the tentativeness of conclusions did not, however, argue for naïve relativism to Schwab. It meant simply that in order to be honest about the nature of science, differences in how the world is viewed by individuals studying the same problem needed to be treated thoroughly. Instruction must teach students “the disciplines of comparison, contrast, choice, and synthesis appropriate to the field in which the diversity takes place” (p. 264).

The pedagogical challenge of such an intellectually sophisticated approach to teaching science was how to get students familiar with and to contemplate the relevance of each these diverse modes of scientific inquiry in the limited time allotted. To Schwab (and his colleagues at Chicago), the answer lay in the analysis of carefully chosen scientific research papers. A scientific research paper is the “bearer of a portion of scientific knowledge in its field,” and “…it ‘illustrates itself’ as an example of scientific investigation” (Schwab 1949, p. 265). All that is required is that the student knows what questions to ask, including what problem is being addressed, the appropriateness of the data, difficulties in obtaining data, how the data were treated, any phenomena that were excluded, and the validity of the conclusions. Each paper “would serve simultaneously to impart subject-matter content and to illustrate aspects of the nature of scientific knowledge at many different levels—from the most specific level at which the paper falls…to the level of science-as-a-whole” (Schwab 1949, p. 251). In the plan developed at Chicago, students would be presented with sets of such papers and with a framework for analyzing them so that they would gain practice in studying those investigations as instances of scientific inquiry, especially how each was similar to and differed from the others.

76.3.3 Science as Constructed Theory

In *Science and Civil Discourse* (Schwab 1956), Schwab elaborates further on the nature of inquiry in science and its importance in liberal education. He says that inquiry is constructive in the sense that conceptions “must be invented…by the investigator” in order to determine what his subject matter and his data will be from the great “complex of things and events” (Schwab 1956, p. 132). According to Schwab, through this process of problem and data selection, the content is inevitably “distorted” and “made incomplete.” Therefore, because of this selecting and narrowing of the problem and consequent narrowing of what is observed, a conclusion in science must be thought of as a “taken something, not an objectively given something” (Schwab 1956, p. 132).

This constructive character of scientific knowledge has implications for the liberal arts curriculum. Schwab argued that if a theory is to be taught as a theory about some aspect of the world, it is also important to be clear about which aspects of the subject are not incorporated into that theory:

> We must have something more in the materials of our curriculum than the theories themselves, for the restrictions which define what the theory is about are not readily found in the theory itself. The theory is only the terminal part of an inquiry. We need what comes before the end…to discover what the theory is a theory of…. (Schwab 1956, p. 133)

This means that the student needs to know that scientific problems are constructed out of a much larger array of possibilities, and they should come to appreciate the choices that are made by scientists in the selection of problems, the selection of observations to be made and data to be collected, and how the data are interpreted in terms of existing theory.

76.3.4 Structure of the Disciplines

Although much of Schwab's work involved efforts to integrate scientific knowledge throughout the liberal arts curriculum by showing the interconnections between subject matters across disciplinary boundaries, he also acknowledged the importance of the separate academic disciplines for curriculum development. In fact, Schwab is often associated with the "structure of disciplines" movement, an effort that became popular in the 1960s to describe the structure of knowledge and the relevance of that structure for school curriculum development and content organization. But Schwab's ideas about "structure" were at least as much about disciplinary modes of thought as they were about how content should be organized. Schwab published a number of essays on the topic, including *Structure of the Disciplines: Meanings and Significances* (Schwab 1964). He found support for the idea of disciplinary structure in Aristotle's distinctions between the theoretical, practical, and productive disciplines and in Auguste Comte's hierarchy of scientific disciplines, starting with physics and progressing to chemistry, biology, and finally the social sciences (Schwab 1960). But he also appreciated that these diverse formulations of disciplinary structure provided support for the truism that "if we classify any group of complex things, we are faced with a wide choice of bases of classification" (Schwab 1964, p. 15). In other words, organizational schemes can be helpful for thinking about the curriculum, but they should not be considered to be fixed and absolute.

Schwab distinguished between the substantive structure of the disciplines (their conceptual organization) and their syntactical structure (how knowledge is generated in each field). He argued that because the two structures are necessarily interconnected, students should be taught the conceptual structure of scientific knowledge in the context of the methods of inquiry that produced that knowledge, and they should be taught the methods of inquiry in terms of the conceptual structures:

> In general then, enquiry has its origin in a conceptual structure… It is this conceptual structure through which we are able to formulate a telling question. It is through the telling

> question that we know what data to seek and what experiments to perform to get those data. Once the data are in hand, the same conceptual structure tells us how to interpret them, what to make of them by way of knowledge. Finally, the knowledge itself is formulated in the terms provided by the same conception. (Schwab 1964, p. 12)

But in no way do these structures represent a fixed body of knowledge or a fixed way of organizing that knowledge:

> The dependence of knowledge on a conceptual structure means that any body of knowledge is likely to be of only temporary significance. For the knowledge which develops from the use of a given concept usually discloses new complexities of the subject matter which call forth new concepts. These new concepts in turn give rise to new bodies of enquiry and, therefore, to new and more complete bodies of knowledge stated in new terms. The significance of this ephemeral character of knowledge to education consists in the fact that it exhibits the desirability if not the necessity for so teaching what we teach that students understand that the knowledge we possess is not mere literal factual truth but a kind of knowledge which is true in a more complex sense. (Schwab 1964, pp. 13–14)

And if we do choose to teach just one conceptual structure, Schwab argues that we should at least be honest about what we are doing:

> But if we do, let it be taught in such a way that the student learns what substantive structures gave rise to the chosen body of knowledge, what the strengths and limitations of these structures are, and what some of the alternative structures are which give rise to alternative bodies of knowledge.
>
> If students discover how one body of knowledge succeeds another, if they are aware of the substantive structures that underlie our current knowledge, if they are given a little freedom to speculate on the possible changes in structures which the future may bring, they will not only be prepared to meet future revisions with intelligence but will better understand the knowledge they are currently being taught. (Schwab 1964, pp. 29–30)

Regarding the specific conceptual structures that should be taught in a liberal arts course in science, Schwab admitted that the topics that he was advocating for the Chicago course showed “no notable departure from those which might be found in one or another conventional ‘survey’ course” (Schwab 1950a, p. 150). For example, the physical science portion of the course included simple Archimedean laws of equilibrium and the lever, phenomena involving chemical and physical change, molecular and atomic theories, and the periodic table. It included concepts of energy, the kinetic molecular theory, the theory of special relativity, and ideas about radiation. In the biological sciences portion of the course, topics included transport and regulation of respiratory gases and the regulation and utilization of food material, the structure of the heart and circulatory system, the levels of organization of organisms, and issues of health and disease. Also included were the developmental history of organisms, Darwinian evolution, Mendelian genetics, embryonic development, and various concepts from the field of psychology.

The reason there were no radical departures from what was traditionally taught in introductory science courses was because the primary focus of the Chicago program was not the content itself but the interconnectedness of knowledge and the nature of scientific inquiry. Much of the content that was taught in traditional survey courses would suffice as long as connections were made between topics and the content was taught in the context of the scientific inquiry that produced it. In the case of physics and chemistry, for example, he said that because concepts of energy are related to various phenomena involving chemical change, “a relation between a problem in physics and one in chemistry is established as illustrative of the unifying function of scientific inquiry” (Schwab 1950a, p. 150). Also, as already noted, original papers would be used to introduce students to both the core ideas of science and to their methods of inquiry, through actual accounts of scientific research. The point is that the science content was seen primarily as a vehicle for teaching about the nature of scientific inquiry rather than as an end in itself. Schwab’s interest in the structure of the disciplines had as much or more to do with the modes of thought that characterized science as it did with the products of that inquiry.

76.4 *Eros* and Education

Although Schwab’s work at the undergraduate level is most often associated with efforts aimed at intellectual development through the liberal arts, he also appreciated the importance of the affective dimension in education, both as a means to achieve intellectual goals and as a proper educational goal itself. In *Eros and Education* (Schwab 1954), he draws on the concept of *Eros* as the psychic energy of creating and wanting that drives students’ desire to learn what is placed in front of them and supplies them with a love of knowledge that makes them want to learn throughout their lifetime. Schwab’s notion of *Eros* is akin to Freud’s idea of the fundamental life instinct that drives humans to create and be productive (Freud 1975/1920). It also bears similarities to Jung’s notion of *Eros* as “psychic relatedness,” particularly as Schwab used the idea to describe the interactions between students and teacher during class discussions (Jung 1982, p. 65).

Schwab believed that *Eros* could be nurtured in an educational setting through classroom discussion. To him, discussion was the embodiment of the intellectual skills that define a liberal education. At its best, classroom discussion draws upon an interpersonal relationship between student and teacher that is characterized by liking and respect. The respect of student for teacher comes from the belief on the part of the student that the teacher has something of value to offer that will enable the student to grow toward intellectual maturity. For both student and teacher, the liking and respect comes from shared participation in a problem of genuine interest to the two of them. When done well, classroom discussion stimulates a love of learning that can last a lifetime.

Schwab argued that the truly educative discussion has three functions: the substantive, the exemplary, and the stimulative functions, representing three liberal education aims of knowledge, power, and affection. First, there must be a specified object of knowledge that the discussion is intended to address. Second, the discussion must involve an activity that leads students to an awareness and appreciation of the method of inquiry employed in the generation of the knowledge. Finally, each discussion must serve to motivate students to engage in the activity so that learning can in fact take place.

Discussion satisfies its substantive function when it is focused on a clear knowledge goal. It satisfies its exemplary function when it engages students in an examination of a variety of methods suitable to the questions being addressed, and the students recognize that people can arrive at differing answers to a problem because of differences in how they formulate the problem, differences in the data they collect relevant to the problem, and differences in how they draw conclusions from those data. Discussion satisfies its stimulative function when the *Eros* is activated, as when a teacher inspires students through accounts of personal experience or allows students to share their own insights and opinions. The result of such a balanced approach is the education of students who have both a creative impulse and a desire to engage in a search for knowledge. Schwab noted that the discussions he envisioned share little in common with the all too familiar undergraduate experience in which the discussion is no more than a reorganizing and rearranging of what the students already know with little new knowledge added.

76.5 Character Education

In addition to recognizing the important connection between intellect and emotion in an educational setting, Schwab was also interested in the role of intellect in the development of personal values, ethical behavior, and character. In an early paper titled *Biology and the Problem of Values* (Schwab 1941), he analyzed the relationship between the teaching of biology and the teaching of values in the context of general education. Schwab began by acknowledging that people have a variety of attitudes about criteria for making value judgments. He said there are some who argue that there are *no* useful criteria for judging which of many ethical systems to choose from, others who say that one person's opinion is as good as another's, and still others who choose to follow the ethical position of the majority. Instead, Schwab says, ethical judgments can be made rational and subject to rational test. Value judgments can be made rational to students by having them learn how to think through and analyze ethical problems in the same way that they think through scientific problems. He says:

> …we can take a leaf from the scientist's notebook. A good scientist does not go into the laboratory "cold" to solve a problem. Instead, he reads the available literature by experts in the field—not to believe, of course, nor to reject but to weigh, consider, and verify.
>
> The same can be done in the field of ethics—we can read the experts from Plato and Aristotle, through Bentham and Hobbes, to Dewey; read then, not to swallow what they have to say, nor to reject it—but to see and evaluate the thought and insight and logic…. (Schwab 1941, p. 94)

One way to teach students this connection between the intellectual and the ethical in science classes is to provide them with controversial issues (Schwab suggests soil and water conservation or other bio-economic issues) and to:

> …take them apart for the student to show him that such programs of action involve both data as to means and judgments as to ends, to let him see what ethical principles must be

> used to decide the issue, and to give him an opportunity to deduce for himself the appropriate application of these principles to the particular problem. (Schwab 1941, p. 96)

In a later paper (Cohen and Schwab 1965), the idea of an intellectual dimension to value judgments, ethical decision making, and character development was applied in the context of religious education. In that paper, Schwab and his coauthor describe efforts to design curricular activities for character development for students in Jewish summer camps while Schwab was chairman of the academic board of the Melton Research Center of the Jewish Theological Seminary. The authors begin by affirming the connection between character and intellect:

> We suspect that one of the chief reasons why educators have been thwarted in devising methods of character education is their failure to consider the possibility that there may be means of advancing the student's character development through his intellect. (Cohen and Schwab 1965, p. 23)

The approach they used was to teach students a familiar set of ethical principles derived from the Bible (e.g., thou shalt not stand idly by while an evil is being committed) and then to ask students to relate these ethical principles to life situations by means of "practical logic" (Cohen and Schwab 1965, p. 24). To Schwab, practical logic involves weighing alternative ethical positions within a logical framework in order to choose the best one. The logical framework provides a structure for deciding which ethical principle is applicable to a particular set of circumstances or for deciding between two or more equally valid but apparently irreconcilable ethical principles.

In one activity, students confront the Biblical dilemma that all of creation is sacred, but yet humans have been given dominion over the earth. They are given a series of situations and asked if they think the action that is described is more consistent with the idea that everything was created for human use and satisfaction or with the idea that everything in nature should be protected by humans because it is sacred and inviolable. The positions that they evaluate range from "every city should have a zoo so that people will have a place to go for picnics" to "we should not…build a dam if this will destroy a beautiful natural vista or displace…wildlife" (Cohen and Schwab 1965, p. 25). These structured activities were meant to provide students with analytical skills that would be useful to them as they applied their logical reasoning to ethical questions. It would give them practice in thinking through real-world cases and experience in using specific analytical structures to identify issues they could then consider when making ethical choices.

Schwab did not believe that there was a single ethical standard that could be used for making value judgments. Rather, ethical inquiry uses the same kind of intellectual approach that empirical inquiry uses. Humans can make ethical judgments using their practical intelligence and in consideration of the consequences of the choices they make.

In 1969, Schwab published *College Curriculum and Student Protest* as a practical example of ethical decision making and the role the college can play in character development. The book was written in response to the student protests of the 1960s and was an attempt to use curricular revision to solve the problems he believed had been created by the existing curriculum. *College Curriculum and Student Protest* takes an analytical approach to solving the problem of student unrest. Who are the protesters? What is it about their education that they are protesting? What could be done differently—both in terms of the content of the curriculum and the way it is taught—to give students greater satisfaction with their college experience or, at least, a more intelligent and informed basis for protest. To each of these questions, he systematically lays out an array of possible answers. He then proposes many of the approaches that he had advocated in his earlier writings. In particular, and especially relevant to the teaching of science, he describes the dissatisfaction that results from "…the neatness and air of inevitability with which we invest our accounts in science textbooks and lectures of the evidences which lead to current theory" (Schwab 1969a, p. 8). As a solution to the alienation that students felt from their college experience, he proposes making better use of the students' own intellectual capabilities by focusing less on the assimilation and use of the products of inquiry and more on how knowledge in each field is acquired. Speaking of how students were being taught, he says:

> Instead of giving experience of the kinds of problems and modes of enquiry characteristic of the field, they provide the student with the experience of assimilating, applying, or otherwise using the fruits of enquiry in the field. Yet these two—assimilation and use as against pursuit of a body of knowledge—are often radically different in the competences they require and the satisfactions they afford. (Schwab 1969a, p. 10)

What students needed, according to Schwab, was experience in the practical art of thoughtful deliberation, opportunities for sharing experiences and ideas, and skill in mutual criticism. Materials should be presented to them not as unqualified assertions but as genuine questions for investigation. And those inquiries should be presented side by side with other inquiries, posing different but similar problems and using different data and arguments so that the student could see the questions, arguments, and conclusions in a broader intellectual context. And students should also have opportunities to engage in the messiness of practical problem solving, not just be presented with problems and the variety of ways of examining and drawing conclusions about those problems. As Schwab put it: "This is essentially the problem of facing the student with 'reality,' that is, of discovering to him the sense and extent to which real cases are not mere instances of general rules or mere members of classes" so that the student can appreciate that "principles are brought to bear on cases only approximately and with great difficulty" (Schwab 1969a, p. 116).

Schwab also argued for having students experience "works in progress," both their own and those of others: "It is one of the most powerful ways—perhaps the only way—to afford experience of the ground of all enquiry: the originating problem, the first idea, the nascent plan, the seminal purpose, from which flow research and scholarship worth the doing" (Schwab 1969a, p. 210). A study of finished products, on the other hand, does not provide a sense of aspects of a problem that are only "half-known" before the project has begun.

Finally, he says, the goal of curricular reform should be to provide students with an intellectual challenge and the opportunity to develop skills in "recovery, enquiry, and criticism appropriate to each discipline." In the sciences, social sciences, history, and philosophy, this means “no ‘truth’ without the evidence and argument which supports it or from which it grows” (Schwab 1969a, p. 183). This includes the presentation of alternative principles, evidence, and interpretation that give fields of study their competing theories and uncertainties. Instead, the curriculum that protesters were reacting to omitted uncertainty and how decisions are made about what evidence should be counted and which theories should be preferred. “Little wonder,” Schwab concludes, “that anxieties, persecution feelings and a wearisome spate of intemperate, stereotyped protest should flood from students’ mouths. Still less should we wonder that they so often cite their unexamined impulsions as sufficient ground for choice and, indeed confuse the one with the other” (Schwab 1969a, p. 16).

76.6 Applying Lessons Learned at Chicago to School Science

Beginning in 1959, after more than 20 years of efforts to integrate science into the liberal arts core curriculum at Chicago, Schwab had an opportunity to contribute to the reform of school science through his association with the Biological Sciences Curriculum Study (BSCS). BSCS had been organized by the American Institute of Biological Sciences in 1958 to reform biology teaching in the country. Schwab became chairman of the Teacher Preparation Committee at BSCS and was responsible for developing plans for the preservice and in-service training of teachers who would be teaching new courses that were part of the reform initiative. Under his leadership, the committee produced a *Teacher’s Commentary* to accompany each of the three versions (blue, yellow, and green) of the BSCS biology texts (Hurd 1961), and he authored the first *Biology Teacher’s Handbook* for BSCS in 1963.

Also in keeping with his interest in precollege science education, Schwab was invited to deliver the Inglis Lecture at Harvard University in 1961. The talk, published as *The Teaching of Science as Enquiry* (Schwab 1962), serves as a summary of his thinking about the nature of science and the teaching of science at the school level. The lecture focused on the nature of scientific investigation, on ways for students to develop an appreciation for science as a process of inquiry, and the intellectual skills involved in inquiry. There were three main themes: First was the importance of offering students a realistic portrayal of the nature of science so that as citizens they would understand that scientific investigations yield theoretical constructions that are tentative and ever-changing. The second focused on the pedagogical approaches that would give students practice in the intellectual skills involved in inquiry so they would be capable of independent critical reasoning throughout their lifetimes. And the third was the idea that science is not just an intellectual activity but also a study of actual events in the world. An educational program, therefore, needs to link the scientific principles and intellectual skills taught in the school curriculum to concrete phenomena in the physical world.

Schwab also argued that schools could play a role in educating the public about the importance of science in society. For citizens to be supportive of science, they must first understand *why* scientific knowledge continues to shift and *why* ideas that were once thought to be true may later be discarded. If the public is expected to support science, they need to understand the revisionist nature of science and appreciate that much of the language of science describes ideas and models, not actual physical reality. To Schwab, the key to having students develop an accurate picture of science was for them to understand that science rests on "conceptual innovation" (Schwab 1962, p. 5) and that scientific understanding changes as new ideas are conceived. This view of science cannot be achieved if students are taught in ways that suggest to them that knowledge is fixed and certain.

In many ways, these ideas about the nature of science are mirrored in Thomas Kuhn's[4] *The Structure of Scientific Revolutions* (Kuhn 1962), published the same year as Schwab's *The Teaching of Science as Enquiry*. Just as Schwab was deeply involved in developing the liberal arts core at Chicago beginning in the 1940s, Kuhn taught a comparable course for undergraduates at Harvard in the 1950s as part of its General Education in Science curriculum. Schwab's thinking did not go quite as far as Kuhn's notions about the incommensurability that results from "paradigm shifts," but a similar idea that significant conceptual shifts occur that make previous thinking obsolete can be seen in Schwab's writing:

> With each change in conceptual system, the older knowledge gained through use of the older principles sinks into limbo. The facts embodied are salvaged, reordered, and reused, but the knowledge which formerly embodied these facts is replaced. There is then, a continuing revision of scientific knowledge as principles of enquiry are used, tested thereby, and supplanted. (Schwab 1962, p. 15)

In Schwab's terms, science enjoys periods of "stable enquiry," during which agreed upon fundamental principles are used to guide research. But occasionally a shift occurs during which the principles that previously guided scientific investigations no longer are relevant. These periods of change are periods of "fluid enquiry." Fluid enquiry is not about filling in the missing pieces of the earlier models and conceptions. Instead, it involves the creation of new conceptions to guide scientific research (Schwab 1962).

Schwab thought that all citizens, not just future scientists, needed to be educated to think in this critical and creative way and that this was a contribution that schools could make to an informed citizenry. Drawing on his experience with undergraduate education at the University of Chicago, he believed this approach to school science would produce leaders who would both understand the nature of scientific inquiry and be able to think reflectively and creatively themselves.

For this approach to be successful, students would have to be active learners, fully engaged intellectually in the study of science. Rather than being told that the textbook and teacher are unquestioned sources of authoritative information, students would be encouraged to challenge teacher and text and to view what was said by them as something to be analyzed and critiqued. The student's attention

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[4] A comparison between Schwab's and Kuhn's ideas, especially the implications of those ideas for science teaching, can be found in *Kuhn and Schwab on Science Texts and the Goals of Science Education* (Siegel 1978).

should not be on scientific statements as words and assertions to be learned, but on "…what the words and assertions are about: the thoughts and the actions of a scientist which have gone into the making of a piece of scientific research" (Schwab 1962, p. 66). It is the responsibility of the teacher to teach the students how to engage in these intellectual activities—what to look for, the kinds of questions to ask, and when to ask them.

To increase the breadth of their thinking about the various ways that scientific statements can be interpreted, students should also be asked to compare answers from different students and make judgments about those answers based on the evidence that is provided in support of them. In this way, the student learns that "…there is room for alternative interpretations of data; that many questions have no 'right' answer but only most probable answers or more and less defensible answers; that the aim of criticism and defense of alternative answers is not to 'win the argument' but to find the most defensible solution to the problem" (Schwab 1962, p. 70).

As he did when writing about undergraduate education at Chicago, Schwab proposed class discussion as the best way to engage school students in challenging intellectual discourse. And as he did for undergraduate students, Schwab suggested that original scientific papers offered "the most authentic, unretouched specimens of enquiry which we can obtain" (Schwab 1962, p. 74). His primary goal for students at the precollege level as with undergraduate students was the development of broad intellectual competence.

76.7 The Practical in Curriculum Development

Toward the end of his long academic career—which included efforts to create a program of liberal studies at the University of Chicago, his work with the Great Books Program with Hutchins and Adler, his work at the Jewish Theological Seminary, and his contributions to curriculum reform in school science at BSCS—Schwab wrote a series of six essays (four were published) that synthesized his understanding of the essential processes involved in curriculum development (Schwab 1969b, 1970, 1971, 1973, 1983). The first, *The Practical: A Language for Curriculum,* was written for the National Education Association's Center for the Study of Instruction and was published in 1969 (Schwab 1969b, 1970). The last was published in 1983, nine years after Schwab had retired from Chicago. That essay was titled *The Practical 4: Something for Curriculum Professors to Do*.

In *The Practical: A Language for Curriculum,* Schwab begins with an indictment of the present state of the curriculum field:

> The field of curriculum is moribund. It is unable, by its present methods and principles, to continue its work and contribute significantly to the advancement of education. …The curriculum field has reached this unhappy state by inveterate, unexamined, and mistaken reliance on *theory*. (Schwab 1970, p. 1)

According to Schwab, whether theories are borrowed from disciplines such as philosophy, psychology, or sociology or constructed explicitly as educational theories of curriculum and instruction, they are "ill-fitted and inappropriate to problems of actual teaching and learning" (Schwab 1970, p. 1):

> Theory, by its very character, does not and cannot take account of all the matters which are crucial to questions of what, who, and how to teach; that is, theories cannot be applied, as principles, to the solution of problems concerning what to do with or for real individuals, small groups, or real institutions located in time and space—the subjects and clients of schooling and schools. (Schwab 1970, pp. 1–2)

Simply put, to Schwab education is much too complex an activity to be captured by a unified theory of teaching and learning. Inevitably, all theories create abstractions or idealizations of the particulars of the real world. And, because human behavior—which is what educational theories theorize about—is so complex, educational theories of necessity leave out much of the variation that occurs in the world. Schwab says: "It follows that such theories are not, and will not be, adequate by themselves to tell us what to do with actual human beings or how to do it" (Schwab 1970, pp. 28–29).

In an earlier essay, *On the Corruption of Education by Psychology* (Schwab 1957), Schwab demonstrated how certain theoretical positions from psychology create problems when applied in educational settings. The three theories he focused on were group dynamism, non-directivism, and autonomism. In the case of group dynamism, the group becomes the determiner of knowledge and the central focus of education; in the case of non-directivism, it is the individual who is supreme as a knowledge maker; and in the case of autonomism, the emphasis is on individuals' struggle for autonomy against the hegemony of society. According to Schwab, in each of these three cases the application of the theory goes well beyond what is reasonable or useful, and leads to practical conclusions that are opposite the others. "All three doctrines, beginning as normative or descriptive views of behavior, end by inventing an epistemology which tailors the intellectual aims of the curriculum to fit the terms of their incomplete theories of behavior" (Schwab 1957, p. 44).

He suggests, instead, that education should be seen as a practical enterprise, having many individual components that need to be analyzed separately, not as a unified activity that can be explained by and organized around a single all encompassing theoretical position. These ideas about the practical in curriculum are consistent with his ideas about the use of practical rationality that pervade all of his work.

It's not that Schwab thought that educational theory was useless or irrelevant, but rather that theory needed to be used judiciously to explain individual aspects of the educational enterprise and without overreaching in its attempt to create a grand synthesis.

He proposes three related and overlapping alternative approaches to a purely theoretic approach: what he calls the practical, the quasi-practical, and the eclectic. First is the *practical*. About the practical, he says: "The subject matter of the practical…is always something taken as concrete and particular and treated as indefinitely susceptible to circumstance, and therefore highly liable to unexpected change: this student, in that school…" (Schwab 1970, p. 3). The method of the practical is deliberation, which is a "complex, fluid, transactional discipline"

(Schwab 1970, p. 5). Deliberation involves the use of practical rationality by paying attention to particular events in particular places, recognizing the importance of the particular context in which education takes place, and having an openness of mind about the range of possible explanations for what takes place in each educational setting.

The *quasi-practical* approach shows particular awareness of the diversity that exists in schools and school communities. It is “an extension of practical methods and purposes to subject matters of increasing internal variety” (Schwab 1970, p. 5). It is *quasi*-practical because of its added complexity, which sometimes renders it less effective and, therefore, less practical, than what was desired. A practical solution might be found for a problem in one part of the system, only to find that it was not really a solution at all because of unforeseen and undesirable effects that the solution has on another part of the system. Thus solving a practical problem in the science portion of the curriculum may create problems in another part of the curriculum. Therefore, solving practical problems in complex systems requires coordination of efforts and sharing of information and expertise beyond what is required in simpler systems.

Finally, the *eclectic* approach is an approach that pays attention to a variety of theories or parts of theories that might be used in a practical analysis to inform particular aspects of curricular decision making, while at the same time being aware of the limitations of those theories. To Schwab, it is not that all theory is useless. But because of their enthusiasm to explain human behavior in general terms, educational theorists often inappropriately use theories to explain more than they in fact do explain, and they recommend or prescribe educational practices that are not warranted. It is important to know what a given theory can explain and what it cannot explain. With an understanding of the limits of each theory, it may be possible to use those theories to explain various parts of the educational experience.

76.8 Schwab’s Legacy

Schwab can rightly be called a humanist, a constructivist, and a Deweyan progressive, and he lent his considerable support to those streams of thought in his educational writing. Regarding his humanism, according to Eliot Eisner, Schwab, along with educators such as Phillip Jackson (*Life in Classrooms,* 1968), helped to initiate a trend toward the “humanization of educational inquiry” through practical rationality, by his acknowledgement of the idiosyncrasies of educational contexts and his valuing of deliberation as “the exercise of the human’s highest intellectual powers” (Eisner 1984, p. 204). He was a constructivist in how he viewed scientific theory as resulting from conceptual innovation, a process by which theoretical structures are constructed and revised in the context of still larger bodies of interconnected observation and theory. Schwab believed that scientists, operating in a milieu of interconnected theory, make choices about what to study, what data to collect, and which theoretical framework to use to make sense of their data. Schwab’s writing in this area is still viewed as exemplary. Regarding his progressivism, Schwab showed great admiration for Dewey's work, as he shows in *Dewey: The Creature as Creative* (Schwab 1953) where he praises Dewey's ideas about the human role in generating truth in both philosophy and science. He also took on the role of apologist for Dewey, explaining misunderstood concepts as he did in *The "Impossible" Role of the Teacher in Progressive Education* (Schwab 1959) where he explains and defends Dewey's notion of the dialectic. Schwab himself was a Deweyan progressive in how he valued informed and reflective practice, in his belief in intellectual growth through the continuous reconstruction of experience, and the importance he placed on science as a way of thinking about the world rather than simply as a body of knowledge of the world.

When we look at his legacy at a finer grain size, the success of some of his more specific proposals for science education is somewhat mixed. Schwab devoted a lifetime to thinking and writing about the role of science in a liberal arts setting, first for undergraduate students and then for students at the precollege level. His recommendations were for rigorous intellectual preparation in science so that students could come to know what is known about the world and how the natural world works, but even more important, how we know what we know. His hope was that such an education would give students the capability and desire to learn throughout their lifetime. Among science educators whose interest is the precollege level, he is most well known and appreciated for the application of these ideas to the school curriculum, especially the work he did at BSCS during the 1960s and his very well-received *The Teaching of Science as Enquiry* (Schwab 1962).

On the surface, it is fair to say that his contributions to general education at the college level were short lived. Efforts to create a common experience for undergraduate students at Chicago and to organize the undergraduate college around that common experience eventually gave way to an organization of the curriculum around the disciplines and a requirement that students specialize in one of those disciplines, the very concerns that motivated the general education movement in the first place. The Chicago plan, which was one of the most radical experiments in general education, initially offered a complete program of general education courses in the undergraduate college, but the pressures for specialization led to a reorganization of that program in 1957, and under the reorganized program students were required to major in one of four academic divisions as a requirement of the degree (Bell 1966).

In a 1963 editorial comment, *A Radical Departure for a Program in the Liberal Arts*, Schwab acknowledged the failure to achieve the goals of general education: "It need hardly be said that the most formidable barrier to an effective program of liberal education at the moment is constituted of the concerted pressures toward specialization" and that "the pressure toward specialization has resulted in acute curtailment of the time allotted to a liberal arts program" (Schwab 1963b, no page number). Schwab offered what he saw as a "radical proposal" that the liberal arts could still be communicated to students through a student's area of specialization if they were offered seminars that focused on the development of core ideas in each of those specialties. Not surprisingly, given the courses he had helped to develop in the 1940s, his *radical* proposal included the idea that the study of the development of core ideas in each field of science could be accomplished by way of the students' own examination and comparison of original papers. But, for the most part, that kind of intellectual treatment of the sciences did not find its way into the undergraduate curriculum in any significant way. The products of science, organized by disciplines, or sometimes through interdisciplinary study, continue to be the primary content of the vast majority of undergraduate level science courses today.

Chicago was hardly alone in its inability to maintain a comprehensive program in general education. By 1950, there had been significant erosion of most general education programs, and by the end of the 1950s, those large-scale, comprehensive efforts had for the most part been abandoned.[5] As Daniel Bell pointed out in *The Reforming of General Education* (1966), Harvard's program, whose development was stimulated by the 1945 publication of *General Education in a Free Society* (Harvard Committee 1945) and mandated by the faculty to take effect in 1949, began to come apart almost immediately. Instead of being required to take common courses in each of the humanities, social science, and natural science and mathematics divisions, as initially proposed, students were given lists of courses in each area that could be taken to meet the general education requirement. As Bell observed, the failure was most evident in the sciences:

> The change from the original intention was sharpest in the sciences. In 1949, a faculty committee headed by Jerome Bruner repudiated the idea that the teaching of science could be done through the history of science or by a case-method approach. Instead of a historical emphasis, the Bruner Committee proposed that a student be given a "knowledge of the fundamental principles of a special science," and an "idea of the methods of science as they are known today." The difference between a general education and a departmental course in science would consist, then, only in the selection and coverage of topics, not in approach. (Harvard Committee 1945, p. 48)

Although the Bruner Committee's arguments revealed a fundamental ideological difference in what the nature of the educational experience in the sciences should be, according to Bell (1966) these grand schemes for general education that Schwab was part of were done in as much by practical problems of staffing as they were by intellectual concerns. It was just too difficult to find faculty who were willing to devote their careers largely, if not completely, to teaching undergraduate students the relationships between knowledge in science and the ways that knowledge was generated. In his commitment to do just that, Schwab was unique.

But even though the general education movement that he was a central part of did not last much beyond mid-century, as a thinker in this area, Schwab's ideas had lasting impact. One of the strongest testaments to his work came from Bell who pointed to two books that were most important to him in thinking about the development of the college curriculum for his 1966 work on general education: "One is Ernest Nagel's (1961) *The Structure of Science*, which lays out a 'logic of explanation' dealing with the nature of inquiry. The other is Joseph J. Schwab's *The Teaching of*

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[5] A number of undergraduate colleges in the United States continue to require a common liberal arts core, although the grand experiments of the first half of the twentieth century at places like Chicago for the most part no longer exist.

Science as Enquiry, which discusses in a wonderfully lucid way the dependence of science upon conceptual innovation, and applies these ideas to the problems of teaching" (Bell 1966, p. xxiv). There is much wisdom to glean from Schwab's writings on a liberal arts approach to the study of science, especially in the value he places on the development of human intelligence through a study of the complexities of human thought and inquiry.

Concerning his contributions to precollege science education, especially the curriculum reforms of the 1960s, some of Schwab's ideas still resonate with us today, but others have been overtaken by ideas that he argued against. For example, his description of the nature of science and its implications for science teaching that appears in his 1961 Inglis Lecture (Schwab 1962) is one of the best expositions that we have, and it can still serve as a model of what science is and how it should be taught. But other of his ideas have been overridden by an emphasis on standardization and accountability, ideas that have recently taken hold as dominant themes of school science education. Beginning in the 1980s, science educators in the United States began to create, with much more precision than they had ever done before, detailed specifications of what all students should know in science and to hold students accountable for those ideas through standards-based assessments. The first national efforts to describe what all students should know began in 1989, in mathematics, with the publication of *Curriculum and Evaluation Standards for School Mathematics* by the National Council of Teachers of Mathematics (1989) and, in science, with the publication of *Science for All Americans* by the American Association for the Advancement of Science (AAAS 1989).

The primary goal of these publications was to provide more clarity about what the goals of the curriculum in these areas should be, including an appreciation for the methods and processes of inquiry that were used in science, but they also helped move science education in the United States toward a standardization of content, at least at the state level. Federal legislation required that all states develop explicit statements of what students should know and to develop tests to assess that knowledge. Although the national level documents included recommendations for the inclusion of the methods and processes of science along with the subject matter content, most state standards and state assessments focused on the details of the content and not on an examination of scientific inquiry.

At first glance, Schwab's writing seems to offer support for such a focus on subject matter. After all, Schwab is linked to the "structure of the disciplines movement," which typically gives primacy to subject matter and how it is organized. But Schwab's focus was not on prescribing particular conceptual structures for students to learn as much as having them analyze competing knowledge structures and how those competing knowledge structures were created. The implication of his approach for curriculum development is that subject matter should be seen as *useful*, in fact *critical* for curriculum development, but that is not the only thing to be considered. As Fox (1985) put it:

> Schwab argues that it is not the role of curriculum to simplify or to parrot a favored or accepted conception of a discipline, but to reflect on what contribution the various conceptions within a discipline can make to the thinking, the feeling and the behavior of the student.

> Thus, he establishes the basis for his distinction between subject matter and subject-matter-for-education. (Fox 1985)

To Schwab, it is true that the selection of subject matter is critical because it is central to understanding a particular field of study and because of its cultural significance. But, when thinking about subject matter for education, curriculum makers also should take account of the demands of the learner, the teacher, and the school environment (milieu) when deciding what to teach. Schwab argues for a balanced approach to curriculum development and warns against the possible corruption of education by placing too much emphasis on subject matter alone (Schwab 1973).

Therefore, although subject matter is essential to understanding the nature of a discipline, the particular details of that subject matter can and should vary depending on the capabilities of the teacher, the interests of the student, and the constraints of the educational environment. What should be included is subject matter that can act as a vehicle for teaching students the syntactic structure of the disciplines, that is, the ways in which particular knowledge has been generated from a range of possible alternatives. Using this approach, students learn that conceptual structures are dynamic and that there is a knowable logic to the decisions that scientists make about the problems they study, the theories they use to drive their investigations, the data they collect, and how they interpret their findings in terms of the theories that drive those investigations. In such a system, students are challenged to appreciate the complexity of scientific knowledge, the range of existing competing theories, and the variety of methodologies used to generate knowledge in the various science fields. As with his recommendations for undergraduate science education, these ideas about how precollege students should learn science are not generally reflected in the dominant mode of instruction in most schools today, where the focus continues to be largely on the content per se.

Schwab was also concerned about the "objectives" focus that was beginning to drive curriculum development. Objectives were a way of specifying with a high degree of precision what all students should know and be held accountable for in various areas of the curriculum (see, e.g., Mager 1962). The approach was often linked to the psychological theory of behaviorism as applied to education. In 1983, after he had retired from the University of Chicago, Schwab published the fourth in his series of essays on the "practical." In that essay, he identified three limitations of using learning objectives to drive curriculum. First, was that objectives tended to:

> …anatomize matters which may be of great importance into bits and pieces which, taken separately, are trivial or pointless. Lists of objectives…anatomize, not only a subject-matter, but teachers' thoughts about it, the pattern of instruction used to convey it, the organization of textbooks, and the analysis and construction of tests. (Schwab 1983, p. 240)

Second, he believed that the lists of objectives were of little use if consideration was not also given to the means and materials available for their implementation: "…reflection on curriculum must take account of what teachers are ready to teach or ready to learn to teach [and] what materials are available or can be devised" (Schwab 1983, pp. 240–241). Third, there must be consideration paid to the unintended consequences that might result from pursuing those objectives, "…not merely how well they yield intended purposes but what else ensues" (Schwab 1983, p. 241). In sum, none of this can be accomplished unless "…ends or objectives are tentatively selected and pursued. Hence, curriculum reflection must take place in a back-and-forth manner between ends and means." According to Schwab: "A linear movement from ends to means is absurd" (p. 241). Here, too, curricular development in the United States is more likely to follow a linear approach than the tentative, iterative, back-and-forth approach that Schwab recommended, in which ends and means are continuously reexamined in relation to each other.

Schwab's criticisms about assessment were similar to those he had for curriculum development, and they were equally broad in scope and practical in nature. He questioned, first, whether it is even possible to create an assessment that is both highly valid in that it conforms to the content of the curriculum and is useful at the same time. He said that such a test lacks "usefulness" because it tells the teacher nothing of what else besides the prescribed curriculum the student might be learning, what alternative constructions of the curriculum might be possible, or how other forms of testing might produce different results. He proposed the use and comparison of different types and forms of testing, which could then serve as multiple embodiments of, or reflections on, the ends and outcomes of education. Testing can communicate information about the curriculum and, therefore, should not be "…mere 'valid,' and therefore static, measures of a static curriculum, but as centers of and foci for the discussion and improvement of…the curriculum, including tests" (Schwab 1950b, p. 281, cited in Westbury and Wilkof 1978). He concluded his essay on testing and the curriculum by saying:

> The end of such analysis is, however, simple. It is to bring into the vivid meaningfulness afforded by contrast what it is that each participant curriculum does and does not do for its students. The ultimate aim is the same as before: to initiate thought, experiment, and improvement of the participating curriculums. (Schwab 1950b, p. 286, cited in Westbury and Wilkof 1978)

Once again, for the most part, this dynamic approach to assessment that Schwab recommended, as a tool for evaluating not only the students' knowledge but also the effectiveness of the curriculum and classroom instruction, is not the approach that is currently used.

76.9 Conclusion

Joseph Schwab was an important figure in science education. He tackled difficult subjects, often in a forceful way. Sometimes he was successful and sometimes he was not. He was often critical of mainstream ideas and the status quo. But in everything he proposed, he tried to make us more open to alternative ideas and more practically rational in how we see the world. As Elliot Eisner said of his former teacher: "He tries to make [life] more intelligent" (Eisner 1984, p. 201). When it came to the content of the science curriculum, he was not concerned so much with the particular subject matter that was learned as that people would continue to love and pursue knowledge throughout their lifetimes and that they would have both the intellectual skills needed to analyze the artifacts of our culture and the ability to analyze the claims that experts and fellow citizens make. Whether aimed at the undergraduate college or at precollege education, his writings leave us with a wealth of ideas about how science education could be better and with a good deal to think about.

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